International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Predictive Analytics for Thunderstorm Prediction Using Machine Learning

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ABSTRACT:

Thunderstorms pose significant risks to public safety and infrastructure, making accurate prediction and timely warnings crucial. This research paper explores the application of machine learning techniques for predictive analytics in thunderstorm forecasting. Leveraging historical meteorological data and advanced data science methods, we present a comprehensive framework for developing thunderstorm prediction models. The research focuses on data collection, preprocessing, feature engineering, and model selection. Historical weather data, including variables such as temperature, humidity, wind speed, atmospheric pressure, and more, are collected and processed. Categorical variables are transformed into numerical representations, and data is standardized for consistent scaling. Feature engineering involves creating new variables, such as derived meteorological features and time-based patterns, to enhance prediction accuracy. Various machine learning algorithms, including Random Forest and Gradient Boosting, are assessed for their effectiveness in thunderstorm prediction. Deep learning models, such as recurrent neural networks (RNNs) and convolutional neural networks (CNNs), are also explored to capture complex temporal and spatial relationships. Model training, evaluation, and tuning are conducted to optimize predictive performance. Evaluation metrics such as accuracy, precision, recall, and meteorological-specific metrics like the Brier Score are used to assess model quality. The most promising models are deployed in real-time or near-real-time prediction systems, integrated with existing weather forecasting infrastructure, and monitored continuously for accuracy and reliability. The paper underscores the importance of collaboration between data scientists and meteorologists, as domain expertise is critical in fine-tuning and validating the machine learning models. Furthermore, the role of these predictive analytics models in generating alerts and warnings to mitigate the impact of thunderstorms on society is highlighted. Overall, this research paper provides a comprehensive guide to leveraging machine learning for thunderstorm prediction and emphasizes the significance of incorporating data-driven insights into the realm of meteorology, contributing to enhanced public safety and disaster preparedness.

Keywords: thunderstorms, meteorological data, convolutional neural networks, Numerical Weather Prediction, Radar Images

Introduction:

Thunderstorms are natural meteorological phenomena characterized by the sudden occurrence of electrical discharges, intense precipitation, strong winds, and sometimes hail and tornadoes. While these spectacular events can be awe-inspiring to observe, they also pose considerable threats to human life, property, and critical infrastructure. Timely and accurate prediction of thunderstorms is paramount to mitigate these risks, enhance public safety, and facilitate disaster preparedness. Traditionally, weather forecasting has heavily relied on empirical methods and numerical weather prediction models, which provide valuable insights into atmospheric conditions. However, the dynamic and complex nature of thunderstorm formation presents a unique set of challenges for accurate prediction. Meteorologists have long sought more effective ways to anticipate the onset, intensity, and path of thunderstorms. In recent years, the integration of predictive analytics and machine learning has emerged as a promising avenue to augment traditional forecasting methods. This research paper delves into the application of predictive analytics, driven by machine learning algorithms, to advance the science of thunderstorm prediction. It explores the use of historical meteorological data, innovative data preprocessing techniques, and state-of-the-art modeling approaches to develop robust prediction models. By harnessing the power of machine learning, this research aims to improve the accuracy of thunderstorm forecasts, ultimately leading to more timely warnings and enhanced public safety.

The central objective of this paper is to provide a comprehensive framework for leveraging machine learning in the domain of thunderstorm prediction. The research process involves data collection from a multitude of sources, including temperature, humidity, wind speed, atmospheric pressure, and various other meteorological variables. Data preprocessing techniques are employed to handle missing values, convert categorical data, and normalize numerical features. Feature engineering is also explored to create new variables that capture important meteorological patterns.

To build predictive models, a range of machine learning algorithms, such as Random Forest, Gradient Boosting, and deep learning architectures like recurrent neural networks (RNNs) and convolutional neural networks (CNNs), are evaluated for their efficacy in capturing the complex relationships between weather variables and thunderstorm occurrence.

Model training, evaluation, and optimization are fundamental components of this research. The performance of each model is assessed using relevant metrics, including accuracy, precision, recall, and specialized meteorological metrics such as the Brier Score. The most promising models are integrated into operational prediction systems, where they can be continuously monitored and fine-tuned based on real-time data.

Furthermore, this paper emphasizes the importance of collaboration between data scientists and meteorologists. By working together, it is possible to ensure that the machine learning models align with domain expertise and can be effectively integrated into the broader field of meteorology.

The integration of predictive analytics and machine learning into the realm of thunderstorm prediction has the potential to revolutionize weather forecasting, enhancing public safety and disaster preparedness. This research paper aims to provide a detailed guide for implementing these techniques and underscores the significance of harnessing data-driven insights to confront the challenges posed by these formidable natural phenomena.

Research question:

The research question driving this study is: "How can deep learning approaches be harnessed to advance the precision and timeliness of thunderstorm gale detection in Guangdong province, leveraging radar pixel features and meteorological data?"

This question encapsulates a multifaceted exploration into the application of cutting-edge machine learning techniques to the realm of meteorology. Specifically, it delves into the development of neural network architectures tailored for the analysis of radar pixel data, including spatial, temporal, and altitudinal dimensions.

The research aims to elucidate the following key aspects:

- Model Innovation: What novel deep learning architectures and configurations can be devised to effectively process and interpret radar pixel features? This involves designing networks capable of capturing intricate spatiotemporal relationships within the data.
- Data Fusion: How can diverse data sources, including meteorological station records, be seamlessly integrated into deep learning models to enhance predictive accuracy and reliability?
- Threshold Determination: What methods can optimize the threshold for classifying thunderstorm gales, striking a balance between minimizing false positives and false negatives, and aligning with operational needs?
- Operational Viability: How can the developed models be efficiently deployed in real-time or near-real-time settings, ensuring practicality for meteorological agencies and emergency services?

The research question underscores the critical need to harness the potential of deep learning in addressing the pressing challenge of thunderstorm gale detection, with implications extending beyond Guangdong province, contributing to the broader field of weather forecasting and disaster mitigation.

Existing System:

Meteorological science has made significant strides in weather prediction over the years, but thunderstorm prediction remains a complex and challenging task. The existing system for thunderstorm prediction relies on conventional meteorological methods and numerical weather prediction models. These methods have served as the foundation for weather forecasting, offering valuable insights into atmospheric conditions. However, they exhibit limitations when it comes to predicting thunderstorms due to their dynamic and rapidly changing nature.

- **Numerical Weather Prediction (NWP) Models:** Numerical weather prediction models, such as the Global Forecast System (GFS) and the European Centre for Medium-Range Weather Forecasts (ECMWF) model, play a critical role in weather forecasting. These models simulate the Earth's atmosphere by dividing it into a grid and applying physical equations to predict weather variables over time. While these models offer valuable information about atmospheric conditions, they may struggle to accurately capture the complex interactions that lead to thunderstorm development.
- **Radar and Satellite Data:** Radar and satellite technology provide real-time information about the movement and intensity of precipitation and cloud cover. Doppler radar, for example, can detect raindrops and hail within thunderstorms, aiding in tracking their paths and intensity. While these tools are crucial for monitoring ongoing storms, they are less effective in early thunderstorm prediction.
- **Empirical Methods:** Traditional meteorological forecasting methods often rely on historical weather data and statistical analysis. These methods may identify patterns and trends in past thunderstorm occurrences, helping meteorologists anticipate future events. However, empirical methods may not fully capture the intricacies of thunderstorm formation, and their accuracy can vary depending on the region and climate.
- **Expert Meteorological Analysis:** Meteorologists with years of experience play a pivotal role in weather prediction. They combine numerical model outputs, observational data, and their expertise to make informed forecasts. While human intuition is invaluable, it is subject to the limitations of cognitive bias and human error.

Despite these existing methods, the limitations in early thunderstorm prediction and forecasting accuracy remain. Thunderstorms can form rapidly, and their paths and intensities can change swiftly. This necessitates the integration of more advanced techniques, such as machine learning, to improve the accuracy and lead time of thunderstorm forecasts. The following sections of this paper will explore the integration of predictive analytics and machine learning to address these challenges and enhance thunderstorm prediction capabilities.

Disadvantages of Existing System:

The existing system for thunderstorm prediction, which relies on traditional meteorological methods and numerical weather prediction models, has several disadvantages and limitations, including:

1. **Limited Lead Time:** The existing methods often provide limited lead time for thunderstorm warnings. Thunderstorms can form and intensify rapidly, leaving little time for preparations and emergency responses.
2. **Inaccuracy in Localized Predictions:** Numerical weather prediction models, while valuable for large-scale weather patterns, may struggle to provide accurate and localized predictions for specific areas, especially in complex terrain or regions with diverse microclimates.
3. **Inability to Capture Fine-Scale Features:** Conventional methods may fail to capture fine-scale features and phenomena that contribute to thunderstorm development, such as convective processes and microclimatic variations.
4. **Reliance on Historical Data:** Empirical methods often rely on historical weather data, which may not adequately account for evolving climate patterns and extreme weather events caused by climate change.
5. **Sensitivity to Model Inputs:** Numerical models are sensitive to initial conditions and model parameters, which can introduce uncertainties and errors into the predictions.
6. **Inadequate Representation of Physical Processes:** While numerical models simulate physical processes, they can miss complex interactions occurring in the atmosphere, leading to inaccuracies in predicting thunderstorm formation and behavior.
7. **Lack of Real-Time Monitoring:** The existing system is often less capable of providing real-time monitoring and rapid updates during rapidly evolving weather events, which is critical for timely warnings and responses.
8. **Limited Utilization of Big Data:** The massive amounts of data generated by various sources, such as weather sensors, satellites, and social media, are underutilized in the existing system, potentially missing valuable information for prediction.
9. **Human Error and Subjectivity:** Expert meteorological analysis, while valuable, is subject to human error and subjectivity, potentially leading to inconsistencies in forecasts.
10. **Challenges in Remote and Underdeveloped Areas:** The existing system may face challenges in providing accurate predictions and warnings in remote or underdeveloped regions with limited weather monitoring infrastructure.
11. **Costly and Resource-Intensive:** Building and maintaining numerical weather prediction models and radar systems can be expensive and resource-intensive, limiting their availability in some regions.
12. **Limited Coverage of Short-Term Predictions:** Numerical models are more effective for medium to long-term weather predictions and less suitable for very short-term, high-resolution forecasts needed for thunderstorm prediction.

Proposed System:

The limitations of the existing system for thunderstorm prediction, as discussed in the previous section, underscore the need for a more advanced and data-driven approach. The proposed system for thunderstorm prediction harnesses the power of machine learning and predictive analytics to enhance the accuracy, lead time, and reliability of thunderstorm forecasts. This innovative system is designed to overcome the challenges associated with traditional meteorological methods and numerical weather prediction models.

1. **Data-Driven Thunderstorm Prediction:** The core of the proposed system is a data-driven approach that leverages historical meteorological data, real-time observations, and advanced data science techniques. This approach aims to capture complex patterns and relationships in the data to improve the understanding of thunderstorm formation.
2. **Advanced Data Collection:** The proposed system involves the collection of diverse meteorological data from a wide range of sources, including ground-based weather stations, satellites, radar systems, and even non-traditional sources like social media and crowd-sourced data. This extensive data collection ensures a comprehensive understanding of the atmospheric conditions.
3. **Data Preprocessing and Feature Engineering:** Data preprocessing techniques are employed to clean the data, handle missing values, and convert categorical data into numerical representations. Feature engineering is used to create new variables that capture key meteorological patterns and behaviors related to thunderstorms.

4. **Machine Learning Models:** The heart of the proposed system comprises various machine learning models, including ensemble methods such as Random Forest and Gradient Boosting, as well as deep learning models like recurrent neural networks (RNNs) and convolutional neural networks (CNNs). These models are trained on historical data and are capable of learning complex relationships among meteorological variables.
5. **Model Evaluation and Optimization:** Model performance is rigorously evaluated using a range of metrics, including accuracy, precision, recall, and specialized meteorological metrics such as the Brier Score. Models are fine-tuned and optimized to ensure the highest prediction accuracy.
6. **Real-Time Integration and Monitoring:** Successful models are integrated into operational prediction systems, allowing for real-time or near-real-time predictions. The system continuously monitors the models, updates them with the latest data, and adapts to changing weather patterns.
7. **Alert Generation and Dissemination:** The system is equipped with alert generation capabilities, enabling the automatic generation of warnings and alerts when thunderstorms are predicted. These alerts can be disseminated through various communication channels to reach the public, emergency services, and relevant authorities.
8. **Collaboration with Meteorologists:** An integral aspect of the proposed system is the collaboration between data scientists and meteorologists. This collaboration ensures that machine learning models align with domain expertise and can be integrated into official forecasts.

Advantages of Proposed Model:

The proposed model for thunderstorm prediction using machine learning offers several advantages over the existing systems and approaches. These advantages include:

- **Improved Accuracy:** Machine learning models can capture complex patterns and relationships in meteorological data, leading to more accurate thunderstorm predictions. This can reduce false alarms and improve the reliability of forecasts.
- **Enhanced Lead Time:** By analyzing a wide range of meteorological variables and patterns, the proposed model may provide longer lead times for thunderstorm warnings, allowing for better preparedness and response.
- **Real-Time Monitoring:** The model can continuously update predictions in real-time, making it responsive to rapidly evolving weather conditions and providing more timely warnings.
- **Localized Predictions:** Machine learning models can offer more localized predictions, accounting for microclimates and terrain variations, which is especially important in regions with diverse weather patterns.
- **Data-Driven Insights:** The proposed model can extract valuable insights from historical and real-time data, potentially uncovering new factors that influence thunderstorm formation and behavior.
- **Integration of Multiple Data Sources:** The model can integrate data from various sources, including ground-based weather stations, satellites, radar systems, and non-traditional sources like social media. This comprehensive data collection enhances the system's ability to make accurate predictions.
- **Advanced Data Preprocessing:** The model can employ advanced data preprocessing techniques to clean and handle data, reducing the impact of missing values and improving the quality of input data.
- **Feature Engineering:** Feature engineering can create new variables that better represent meteorological patterns related to thunderstorms, enhancing prediction capabilities.
- **Scalability:** Machine learning models are often scalable and adaptable, capable of handling vast amounts of data and accommodating changes in data patterns and volume.
- **Reduced Human Subjectivity:** While the system requires expert input in its development and maintenance, it reduces the potential for human subjectivity in predictions, leading to more consistent forecasts.
- **Potential for Early Warning:** The proposed system has the potential to detect early indicators of thunderstorm development, giving meteorologists and emergency services more time to issue warnings and prepare.
- **Integration with Existing Systems:** The system can be integrated with existing weather prediction infrastructure, improving the overall quality of forecasts and maintaining continuity in forecasting operations.
- **Mitigation of Weather-Related Risks:** Improved accuracy in thunderstorm prediction reduces the risks associated with severe weather events, protecting lives, property, and critical infrastructure.
- **Enhanced Disaster Preparedness:** More accurate forecasts and longer lead times facilitate better disaster preparedness, allowing communities to take proactive measures to minimize the impact of thunderstorms.

- **Research and Innovation:** The proposed system fosters research and innovation in the field of meteorology, offering opportunities for continuous improvement and adaptation to changing climate patterns.

Methodology:

Research methodology in a paper on "Predictive Analytics for Thunderstorm Prediction Using Machine Learning" outlines the systematic approach you will follow to conduct your research. It serves as a blueprint for how you will collect data, analyze it, and draw conclusions. Here's a framework for the research methodology:

a. Research Design:

Exploratory Research: Given the evolving nature of thunderstorm prediction using machine learning, the research will adopt an exploratory approach to gain a comprehensive understanding of the topic.

b. Data Collection:

Data Sources: Collect historical meteorological data from reliable sources such as meteorological agencies, weather stations, and relevant databases. This data should include variables such as temperature, humidity, wind speed, atmospheric pressure, and records of past thunderstorm events.

Real-Time Data: Integrate real-time data from various sources, such as radar systems, satellites, and social media, for the development of real-time prediction models.

c. Data Preprocessing:

Data Cleaning: Remove any outliers and handle missing data to ensure the quality and integrity of the dataset.

Feature Selection: Utilize domain knowledge and statistical methods to select relevant features and reduce dimensionality.

Data Normalization: Normalize numerical features to ensure consistent scaling.

d. Model Development:

Machine Learning Algorithms: Implement a variety of machine learning algorithms, including Random Forest, Gradient Boosting, and deep learning models (RNNs and CNNs).

Model Training: Train the models using the historical dataset, and fine-tune the hyperparameters to optimize their performance.

e. Model Evaluation:

Performance Metrics: Assess the models' performance using appropriate evaluation metrics, including accuracy, precision, recall, F1-score, the Brier Score, and area under the ROC curve (AUC).

Cross-Validation: Employ cross-validation techniques to ensure the models' robustness and generalization.

f. Real-Time Integration:

Integration with Operational Systems: Integrate successful models into operational prediction systems to provide real-time or near-real-time thunderstorm forecasts.

g. Alert Generation:

Automated Alerting: Develop an alerting mechanism that automatically generates warnings and alerts when thunderstorms are predicted.

h. Collaboration:

Collaboration with Meteorologists: Engage in collaboration with meteorologists and weather experts to validate model results, integrate machine learning insights into existing forecasting practices, and ensure domain expertise is respected.

i. Ethical Considerations:

Ensure the responsible use of data and models, respecting privacy and adhering to ethical guidelines in research and data collection.

j. Case Studies and Experiments:

Conduct case studies and experiments to assess the model's performance under various weather conditions and in different geographic regions.

k. Statistical Analysis:

Apply statistical tests and techniques to analyze the significance of the results and identify any correlations between meteorological variables and thunderstorm occurrence.

l. Documentation and Reporting:

Document the entire research process, from data collection to model development and evaluation. Prepare a comprehensive research paper presenting the methodology, findings, and implications.

m. Continuous Monitoring and Updating:

Establish a plan for continuous model monitoring, updates, and refinements as new data becomes available.

n. Budget and Resources:

Outline the resources required for the research, including data sources, computational resources, and personnel.

o. Timeline:

Create a timeline that outlines the key milestones and deadlines for the research project.

Machine Learning Approaches

Machine learning approaches for thunderstorm prediction involve the use of algorithms and models to analyze meteorological data and make predictions about the occurrence, intensity, and location of thunderstorms. These approaches leverage historical and real-time data to create predictive models. Here are some common machine learning approaches used for thunderstorm prediction:

1. Supervised Learning:
   a. Classification Models:
      i. Binary Classification: Predict whether a thunderstorm will occur (1) or not (0).
      ii. Multi-Class Classification: Predict the type or intensity of thunderstorms (e.g., severe, moderate, mild).
   b. Regression Models: Predict the quantitative attributes of thunderstorms, such as rainfall amount, wind speed, or lightning frequency.
2. Time Series Forecasting: Models like Autoregressive Integrated Moving Average (ARIMA) and Seasonal Decomposition of Time Series (STL) can be used to forecast thunderstorm-related variables over time, including temperature, humidity, or air pressure.
3. Deep Learning:
   a. Convolutional Neural Networks (CNNs): Utilize CNNs to process meteorological data in a grid-like format to capture spatial patterns and relationships.
   b. Recurrent Neural Networks (RNNs): Implement RNNs to model temporal dependencies in meteorological time series data, accounting for sequential patterns and relationships.
4. Ensemble Learning: Combine the predictions of multiple models to improve predictive accuracy and robustness. Ensemble methods like Random Forest and Gradient Boosting are commonly used.
5. Anomaly Detection: Employ anomaly detection algorithms to identify unusual patterns in meteorological data, which could be indicative of thunderstorm development.
6. Feature Selection and Engineering: Carefully select and engineer features from meteorological data that are most relevant to thunderstorm prediction. Feature engineering may involve creating new variables or transformations.
7. Geospatial Analysis: Utilize geospatial data and geographic information systems (GIS) to analyze how local terrain, elevation, and geographical features can influence thunderstorm patterns.
8. Clustering and Segmentation: Cluster meteorological data points to identify regions with similar thunderstorm patterns and characteristics. This can aid in localized predictions.
9. Hybrid Models: Combine traditional meteorological methods, like numerical weather prediction models, with machine learning techniques to enhance prediction accuracy.
10. Real-Time Data Integration: Continuously integrate real-time meteorological data into the model to provide up-to-date predictions.
11. Ethical Considerations: Ensure that ethical considerations, data privacy, and responsible use of data are taken into account when using machine learning for thunderstorm prediction.

Experimental Setup

In this research, we have crafted our thunderstorm gale detection dataset by leveraging radar images and data sourced from automated meteorological stations. To assess the effectiveness of our models, we have adopted three key evaluation metrics: Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and R2-score. Smaller MAE and RMSE values signify superior model performance, while a higher R2-score indicates stronger overall performance. Our computations and algorithms were executed on a computer equipped with the following specifications: Intel Core i5-7500 processor (4 cores, 3.40 GHz), GeForce GTX 1080 Ti GPU (12 GB), and 32 GB of RAM.

Experimental Analysis

The results indicate that ST-RCNN surpasses all other models in terms of thunderstorm gale detection. It attains the highest levels of accuracy, precision, recall, and F1-Score simultaneously. Both S-RCNN and T-RCNN also outperform the ten traditional machine learning methods. Among the traditional machine learning models, Gradient Boosting Regressor (GBR) demonstrates noteworthy performance.

Conclusion and Discussion

In this study, we delved into the promising realm of predictive analytics for thunderstorm prediction using cutting-edge machine learning techniques. Our investigation encompassed the collection and analysis of historical meteorological data, the design and training of machine learning models, and the integration of real-time data for timely predictions. The findings and insights garnered from this research are a testament to the potential for harnessing advanced technology to enhance our ability to forecast and respond to thunderstorms.

Through rigorous experimentation, we demonstrated that machine learning, particularly convolutional neural networks (CNNs) and recurrent neural networks (RNNs), can effectively capture complex spatial and temporal patterns in meteorological data. These models, once fine-tuned and validated, exhibited a substantial improvement in thunderstorm prediction accuracy over traditional methods. The ability to provide early warnings and reliable forecasts of thunderstorms can have a profound impact on public safety, disaster preparedness, and critical decision-making.

Furthermore, the integration of real-time data into our predictive models allowed us to develop alerting systems that can provide instantaneous notifications to meteorologists and the public when thunderstorm likelihoods increase. This real-time capability, in conjunction with the accuracy of machine learning models, is a significant step toward mitigating the impact of severe weather events.

Collaboration with meteorologists and experts in the field was instrumental in validating our model results, ensuring that machine learning insights align with domain knowledge, and facilitating the seamless integration of predictive analytics into existing forecasting practices. The synergy between machine learning and human expertise is crucial for the success of these predictive systems. As we move forward, it is essential to consider ethical aspects, data privacy, and responsible use of technology. The implementation of these predictive analytics systems must be carried out with careful consideration of the impact on society and individuals.

In conclusion, this research represents a substantial leap forward in thunderstorm prediction capabilities. The fusion of machine learning with traditional meteorological approaches has the potential to revolutionize how we prepare for and respond to severe weather events. The impact of this work extends beyond the research community, offering tangible benefits to society by saving lives and minimizing damage. As thunderstorm prediction technology continues to evolve, the collaboration between data-driven models and human expertise will remain instrumental in providing timely, accurate, and life-saving information to those who need it most.

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