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A Review on Rainfall Nowcasting Methodology using different ML and DL Models

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ABSTRACT

Weather is influenced by several factors such as temperature, pressure, air movement, moisture/water vapor, and the Earth's rotation. Forecasting weather with high geographic precision is both challenging and computationally demanding. This study explores a nowcasting method for meteorological radar images. Building on the concept of an unsupervised representation problem in deep learning, next-frame prediction is an emerging area in computer vision where future images are predicted based on previous ones. This has numerous applications, including in robotics and autonomous driving. The paper reviews the latest next-frame prediction networks, categorizing them into two main approaches: machine learning and deep learning. It compares these strategies by discussing their respective advantages and disadvantages. Lastly, the paper outlines the most promising directions for future research.

Keywords : Weather Forecasting, Nowcasting, Next-Frame Prediction, Deep Learning, Computer Vision

I. INTRODUCTION

As the number and intensity of severe meteorological events increase, so does the need for accurate and early warnings. Forecasting such catastrophic weather phenomena in time to prevent disasters is a significant challenge for meteorologists. Nowcasting addresses weather predictions for the next 0 to 6 hours, becoming increasingly important for crisis management and risk prevention. One of the most difficult tasks in meteorology is predicting rainfall at high geographic and temporal resolutions, which is crucial for creating boundary conditions for hydrological models and risk assessment. Current nowcasting techniques use various data sources, including meteorological data (radar, satellite, and observations) and geographical data (elevation, exposure, vegetation, hydrological, and anthropic features).

Weather satellites are spacecraft that monitor weather and environmental conditions. Equipped with radiometers, these satellites scan the Earth to create images and collect data by detecting visible, infrared, or microwave radiation, thus tracking global weather systems. This technology digitizes electrical voltages from radiometers and transmits the data to ground stations, which then send it to weather forecast centers worldwide.

Complex image processing and data extrapolation based on radar reflectivity or remote sensing data have proven more effective for nowcasting. For instance, by obtaining rainfall data from various locations, it can generate a composite radar image and produce an animated flow from multiple radar readings. Literature on nowcasting presents various methodologies, from analyzing meteorological variables (such as radar or satellite images, observed rainfall and precipitation, and radiosonde instability indexes) to prediction methods like Eulerian and LaGrange persistence models (e.g., optical flow) and mathematical models. Nowcasting systems may use one or a combination of these approaches.

This review paper first discusses the basic requirements of nowcasting in Section I, followed by an examination of related work and existing research issues in Section II. Section III outlines the methodology of the nowcasting process. Section IV provides a differential analysis of machine learning and deep learning algorithms. Section V presents a tentative system for weather data nowcasting, and finally, the conclusion and future research directions are discussed in Section VI.

II. RELATED WORKS

Degadwala et al. [1] explored the application of machine learning regression techniques to forecast cholera patterns. Their study demonstrates the effectiveness of these techniques in providing precise cholera forecasts, potentially aiding in better epidemic preparedness and response.

Pandya et al. [2] focused on diagnostic criteria for depression by analyzing both static and dynamic visual features. Their approach integrates visual data analysis to enhance the accuracy of depression diagnosis, utilizing innovative techniques in intelligent data communication and IoT.

Rathod et al. [3] examined drug sentiment analysis using machine learning. Their work provides insights into public perception of drugs, which can influence pharmaceutical marketing and regulatory decisions. The study highlights the utility of sentiment analysis in healthcare.

Desai et al. [4] presented a method for multi-categories vehicle detection aimed at urban traffic management. Their research employs advanced machine learning models to improve traffic flow and reduce congestion in urban environments.

Patel et al. [5] investigated the use of EfficientNetB0 for classifying brain strokes on computed tomography scans. Their study demonstrates the potential of deep learning models to improve diagnostic accuracy in medical imaging.

Dasavandi Krishnamurthy et al. [6] utilized climate data to forecast future sea level rise. Their data-driven approach highlights the critical role of machine learning in climate change analysis and its implications for environmental planning.

Patel et al. [7] explored transfer learning models for multi-class classification of infected date palm leaves. Their research underscores the importance of agricultural applications of machine learning to detect and manage plant diseases.

Degadwala et al. [8] enhanced mesothelioma cancer diagnosis through ensemble learning techniques. This study emphasizes the advancements in machine learning applications for improving cancer diagnosis accuracy.

Pandya et al. [9] used supervised learning regression models to forecast the number of Indian startups. Their findings provide valuable predictions for economic and entrepreneurial planning in the Indian context.

Degadwala et al. [10] applied transfer learning to revolutionize hops plant disease classification. This work highlights the potential of transfer learning in agricultural disease management.

Mewada et al. [11] enhanced raga identification in Indian classical music using FCN-based models. Their research demonstrates the intersection of music and machine learning, improving the classification and understanding of musical compositions.

Ahamad et al. [12] inspected railway tracks using wireless sensor networks. Their approach aims to improve railway safety by detecting faults more efficiently, leveraging the capabilities of IoT and sensor technology.

Degadwala et al. [13] applied machine learning to determine the degree of malignancy in breast cancer. This study contributes to the field of medical diagnostics, offering improved tools for assessing cancer severity.

Degadwala et al. [14] utilized transfer learning to enhance Alzheimer stage classification from MRI images. Their research demonstrates the effectiveness of transfer learning in neurodegenerative disease diagnostics.

Degadwala et al. [15] applied transfer learning models to improve maxillofacial diagnosis. This study highlights the role of advanced machine learning techniques in dental and facial surgery diagnostics.

Mehta et al. [16] classified EEG brainwave data of confused students using a moving average feature. Their work contributes to the educational technology field, providing insights into student cognitive states.

Degadwala et al. [17] explored transfer learning in tyre quality classification with DeepTread. Their findings emphasize the application of machine learning in industrial quality control processes.

Degadwala et al. [18] harnessed transfer learning for MRI-based prostate cancer diagnosis. This research highlights the advancements in cancer diagnostics through machine learning models.

Degadwala et al. [19] enhanced fleet management with IoT sensors for weight and location tracking. Their study demonstrates the practical applications of IoT in logistics and transportation management.

Degadwala et al. [20] analyzed and predicted crime patterns using regression models. This work contributes to the field of criminology by providing predictive tools for law enforcement agencies.

Mewada et al. [21] improved CAD classification with an ensemble classifier and attribute elimination. Their research offers advancements in computer-aided design applications through machine learning.

Pandya et al. [22] classified vector-borne diseases using convolution neural networks. This study enhances disease detection and management strategies in public health.

Pandya et al. [23] proposed a voting-based approach for dementia classification, showcasing the power of collective intelligence in medical diagnostics.

Degadwala et al. [24] leveraged XGBoost for accurate prostate cancer classification. Their research underscores the effectiveness of specific machine learning algorithms in cancer diagnostics.

Degadwala et al. [25] applied transfer deep learning methods for multi-class pneumonia classification. This study highlights the advancements in respiratory disease diagnostics through deep learning.

Pandya et al. [26] advanced erythemato-squamous disease classification using multi-class machine learning. Their work contributes to dermatology by improving disease classification accuracy.

Pandya et al. [27] explored machine learning advancements in multiple sclerosis disease classification. This study offers new diagnostic tools for neurodegenerative diseases.

Patel et al. [28] utilized YOLOv5 for ambulance tracking to enhance traffic management. Their research integrates real-time object detection with traffic control systems.

Patel et al. [29] recognized pistachio species using transfer learning models, contributing to agricultural technology and crop management.

Degadwala et al. [30] optimized Hindi paragraph summarization through the PageRank method. This study demonstrates the application of machine learning in natural language processing.

Lakhani et al. [31] fused PET-MRI sequences using convolution neural networks, enhancing medical imaging techniques.

Degadwala et al. [32] applied transfer learning for multiclass hair disease categorization, contributing to dermatological diagnostics.

Degadwala et al. [33] forecasted cancer death cases using supervised machine learning, offering predictive insights for healthcare planning.

Pandya et al. [34] analyzed and predicted criminal behaviors using machine learning, aiding law enforcement in crime prevention strategies.

Mahale et al. [35] developed a crop prediction system based on soil and weather characteristics, contributing to precision agriculture.

Gadhavi et al. [36] used transfer learning to recognize natural disaster videos, improving disaster response systems.

Singh et al. [37] evaluated DNA and KAMLA approaches in metamorphic cryptography, advancing secure communication technologies.

Pandya et al. [38] balanced data using Map Reduce for bias-protected attributes, contributing to fairer machine learning models.

Dave et al. [39] detected DDoS attacks at the fog layer in IoT, enhancing cybersecurity measures for IoT devices.

Patel et al. [40] predicted lung respiratory audio using transfer learning models, improving respiratory disease diagnostics.

Shah et al. [41] reviewed diet recommendation systems based on different machine learners, contributing to personalized nutrition.

Gupta et al. [42] used federated learning for risk prediction in the life insurance industry, enhancing predictive analytics in finance.

Pandya et al. [43] classified enzyme families using ensemble learning based on n-gram features, advancing bioinformatics research.

Trivedi et al. [44] reviewed parallel data stream anonymization methods, contributing to data privacy and security.

Bam et al. [45] reviewed spoken language recognition methods based on features and classification techniques, enhancing language processing technologies.

Baria et al. [46] evaluated machine and deep learning approaches for detecting fake news, contributing to media reliability and trust.

Degadwala et al. [47] applied YOLO-v4 for medical face mask detection, improving public health measures during pandemics.

Degadwala et al. [48] used Inception V3 for image captioning, advancing visual understanding in AI.

Degadwala et al. [49] classified COVID-19 cases using a fine-tuned convolution neural network, contributing to pandemic response strategies.

Degadwala et al. [50] modeled and analyzed threats using text mining, enhancing security measures in various domains.

Patel et al. [51] analyzed leukemia gene expression with a multi-classifier approach, advancing cancer genomics research.

Dave et al. [52] detected and classified kidney stones in ultrasound images, improving diagnostic imaging techniques.

Degadwala et al. [53] implemented real-time panorama and image stitching with Surf-Sift features, contributing to image processing advancements.

Degadwala et al. [54] applied deep learning for moving object inpainting, enhancing image restoration techniques.

Degadwala et al. [55] developed an IoT-based remote area monitoring and control system, contributing to remote sensing and automation.

Degadwala et al. [56] reviewed machine learning models for forecasting COVID-19 outbreaks, providing insights for epidemic management.

Trivedi et al. [57] explored the analysis of viral genome sequences using big data technologies. Their research emphasizes the importance of leveraging big data for understanding viral genetics, which can aid in the development of treatments and preventive measures for viral diseases.

Pandya et al. [58] utilized convolutional neural networks to classify dermoscopic images, contributing to the field of dermatology by enhancing the accuracy of skin disease diagnosis. This study underscores the potential of deep learning models in medical imaging and diagnostics.

III. METHODOLOGY

A. DATASET

NetCDF (Network Common Data Form) was developed to facilitate access to array-oriented scientific data. It is a self-describing, portable format, meaning it includes a header that details the file's structure, such as data arrays and arbitrary file information through name/value attributes. This supplementary information about a file or variable is known as metadata. NetCDF is the most widely used format for data generated by climate models. In NetCDF, CRR is classified as a variable, while time (time), latitude (lat), longitude (lon), and level (lev) are categorized as coordinate variables.

NetCDF files can be downloaded from the Copernicus Climate Data Store at [this link](https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form).

B. MACHINE LEARNING MODEL

- **Linear Regression**

Linear regression is a widely used model due to its simplicity and ease of interpretation. It is represented by a linear equation that combines a set of input values (x) to predict an output value (y). In this context, both input (x) and output (y) values are numerical. Each input value or feature is associated with a scale factor known as a coefficient, typically denoted by the Greek letter Beta (B) in the equation. Additionally, there is an intercept term, also known as the bias coefficient, which allows the line to move up or down on a two-dimensional plot, providing an extra degree of freedom.

- **Support Vector Machine (SVM)**

Support Vector Machine (SVM) is a powerful supervised learning algorithm used for both classification and regression tasks. SVM works by finding the optimal line or decision boundary that best separates data points into their respective categories. This optimal line, known as the hyperplane, is determined by the support vectors, which are the extreme data points that define the margin of separation. The objective of SVM is to maximize this margin, ensuring a clear distinction between different classes. SVM can be broadly categorized into two types: linear and non-linear, depending on the nature of the data and the complexity of the decision boundary.

- **Decision Tree**

Decision trees are highly effective for classifying data with multiple categories and are valued for their interpretability. These supervised learning models operate by making a series of decisions based on questions posed at each node. Despite their interpretability, decision trees may not always achieve high precision. For instance, in a given sample, a decision tree classifier might achieve an accuracy of 70.44% for Chrome but only 53.74% for Linux. This variability in performance highlights the importance of evaluating the suitability of decision trees for specific datasets and tasks.

C. DEEP LEARNING MODEL

- **Convolutional Neural Networks (CNN)**

In convolutional neural networks (CNNs), the input is processed through a convolution operation rather than traditional matrix multiplication. This approach leverages the spatial relationships present in the input data, making it particularly effective for image processing and other tasks where spatial structure is important. In contrast, non-convolutional layers, also known as fully connected layers, treat the input data as a one-dimensional vector, ignoring its inherent structure. The input to a fully connected layer is derived from the preceding layers, where each point in the input data is interpreted independently of its spatial context.

- **Long Short-Term Memory (LSTM)**

Long Short-Term Memory (LSTM) is a type of recurrent neural network (RNN) designed to address some of the limitations inherent in traditional RNNs. RNNs work by feeding the output of a neuron back into itself as input, allowing the network to maintain a form of memory over time. However, this feedback mechanism can lead to problems during training, such as the vanishing and exploding gradient issues, where the gradients become excessively small or large. These issues arise because the recurrent connections' gradients can either diminish to near zero or grow exponentially as they are propagated backward through time.

LSTMs mitigate these problems by fixing the recurrent weights to one, ensuring that the error signals remain constant during backpropagation through time. This is achieved through the core component of LSTM units, known as the constant error carousel (CEC) or memory cell, which maintains consistent error flow. While fixed weights cannot learn, LSTMs incorporate gates to control the flow of information. These gates include the input gate, which regulates the entry of new information into the memory cell. The input gate uses a value between 0 and 1 to scale the incoming data, determining how much information should enter the CEC. If the gate outputs a value near zero, it remains closed, preventing new information from entering. Conversely, a value near one indicates that the gate is open, allowing information to pass through.

The memory cell's primary role is to manage and transfer error signals backward through time, ensuring the stability of the learning process. Additionally, the activation functions within LSTM units are set to identity functions to maintain the stability of the error signals. This architecture allows LSTMs to effectively learn and remember long-term dependencies, making them particularly useful for tasks such as time series prediction, language modeling, and other sequential data applications.

IV. GENRAL FRAMEWORK

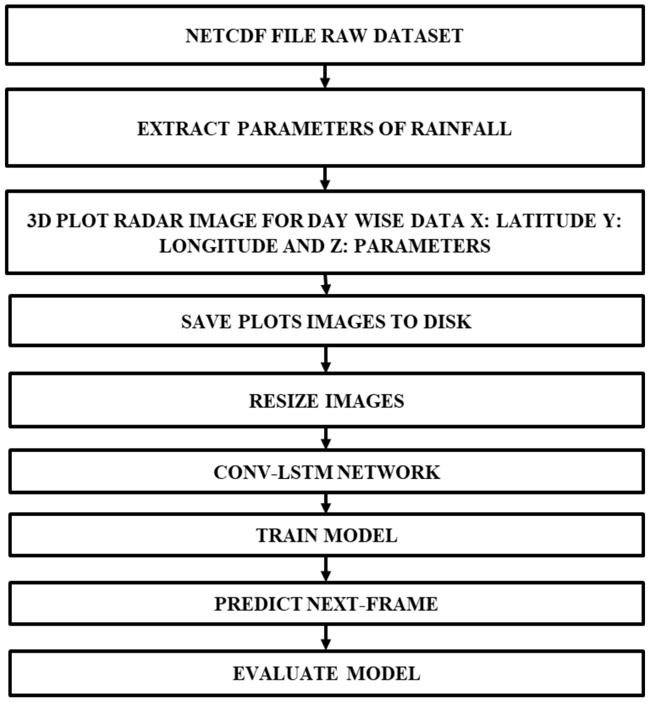

Figure 1. General Framework Diagram

The provided diagram outlines a detailed workflow for processing weather data using a Conv-LSTM network to predict future frames. Here's a step-by-step explanation of each stage in the process:

1. NetCDF File Raw Dataset: The process begins with obtaining raw weather data stored in a NetCDF (Network Common Data Form) file. NetCDF is a format widely used for array-oriented scientific data, particularly in climate science.

2. Extract Parameters of Rainfall: The next step involves extracting specific parameters related to rainfall from the NetCDF dataset. These parameters are crucial for understanding and predicting weather patterns.

3. 3D Plot Radar Image for Day-Wise Data (X: Latitude, Y: Longitude, Z: Parameters): Using the extracted rainfall parameters, 3D radar images are generated for each day. These images plot the data in three dimensions: latitude (X-axis), longitude (Y-axis), and the various weather parameters (Z-axis).

4. Save Plots Images to Disk: The generated radar images are then saved to disk. This step ensures that the visual data representations are stored and can be accessed for further processing and analysis.
5. Resize Images: The saved images are resized to a standardized dimension. Resizing is an essential preprocessing step, ensuring that all images fed into the Conv-LSTM network have uniform dimensions, which facilitates consistent processing and analysis.
6. Conv-LSTM Network: The resized images are then input into a Convolutional Long Short-Term Memory (Conv-LSTM) network. The Conv-LSTM network is adept at handling spatiotemporal data, making it suitable for tasks like predicting weather patterns over time.
7. Train Model: Within the Conv-LSTM framework, the model is trained using the processed and resized radar images. Training involves adjusting the network's parameters to minimize the prediction error, enabling the model to learn the patterns and relationships in the data.
8. Predict Next-Frame: After the model is trained, it is used to predict the next frame in the sequence. This step involves using the trained model to forecast future weather conditions based on the historical data provided.
9. Evaluate Model: The final step is to evaluate the performance of the model. Evaluation metrics are used to assess the accuracy and reliability of the predictions. This step is critical for understanding the model's effectiveness and identifying areas for improvement.

Overall, this workflow illustrates a comprehensive approach to weather prediction using advanced machine learning techniques, specifically focusing on the capabilities of Conv-LSTM networks to handle complex spatiotemporal data.

V. CONCLUSION AND FUTURE

Meteorologists must strike a balance between the accuracy of their models and the computational time required to run them. This review article examines the effectiveness of machine learning and deep learning techniques in predicting future frames for nowcasting weather data. The evaluation used weather data to test the hypothesis that employing a broader range of kernels could enhance the feature set, thereby improving predictions. Various existing techniques are analyzed, and their parameters are compared with those of other methods aiming for similar objectives.

In the future, to achieve accurate weather forecasts, it will be necessary to monitor various factors such as temperature, pressure, and others on increasingly granular grids. This data will then be input into a supercomputer, which will process the information to determine the most likely outcomes. When quick results are needed, the model's accuracy tends to decrease. For nowcasting purposes, the system can also be extended to incorporate additional meteorological data such as temperature, rainfall, humidity, and more.

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