MACHINE LEARNING APPLICATIONS IN CLIMATE MODELING AND WEATHER FORECASTING

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Abstract

This work focuses on applying machine learning in both forecasting of the weather and in climate modeling. This paper reviews literature on the current trends with reference to the efficiency of machine learning to enhance the performance and future prediction of computational methods. The assessment of a number of machine learning methods for finding short and long term predictions is attempted in the study using ensemble methods and neural networks. The implementation and deployment concerns are included with the approaches to data collecting, processing, and model making. The conclusions imply that, from time to time, machine learning models outperform conventional physics-based models and seem to have a special advantage in predicting short-term conditions. The climatic forecasts for long-term and the events of extreme weather still present challenges, nevertheless.

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TABLE OF CONTENTS

Introduction

The Machine learning approaches of this current era have made a revolutionary change for the better in some of the fields like Weather Forecasting and Climate Modeling. This novel approach has new possibilities to improve the detail, accuracy, and scope of the climate simulations and extreme weather predictions. At present, the complexity and scope of atmospheric systems are beyond the power of analytical quantities that can be employed in physics-based models. It is here that machine learning appears to be a magic opportunity of participating in vast amounts of data and computational resources trying to discover relationships and connections. This paper discusses how machine learning has been harnessed in the current state of weather forecasting and climate modeling, the challenges faced, and the prospects for the future.

Literature Review

Application of Machine Learning in Weather Forecasting

According to the author (Holmstrom*et al.* 2016): The explanation of how machine learning methods are used in this field with specific reference to weather forecasting is done in this paper. The authors also note that even now, the main concept of the objective method of weather forecasting, which is based on the physical modeling of the atmosphere, is hopelessly inaccurate and subject to random fluctuations which can make it wholly unreliable over long tracts of time. The method based on machine learning is believed to be less sensitive to the disturbances and might provide more precise forecasts for the future weather conditions.

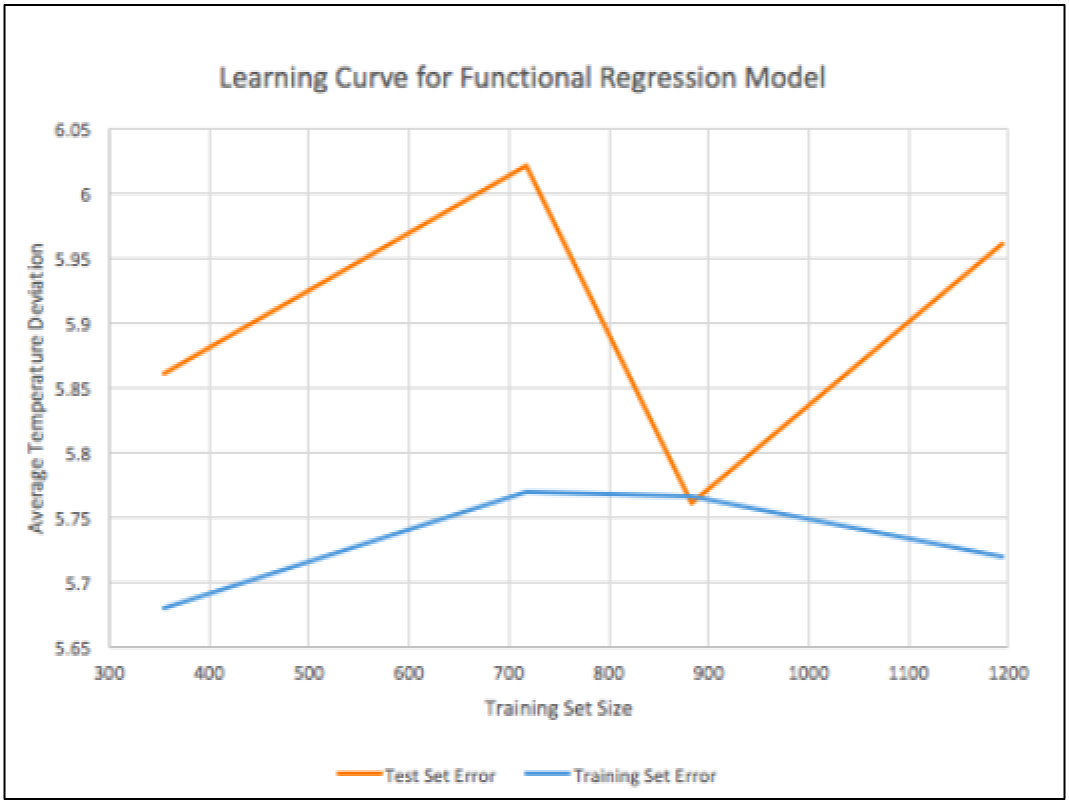

Figure 1: Visualization of learning curve for regression model

(Source: Holmstrom*et al.* 2016)

Concretely, the objective of the study was to predict the maximum and minimum temperatures during the successive seven day period on the basis of the data concerning the climate of the two previous days. There were two models used: there exists a functional regression model variant and linear regression model. The latter was designed to capture the temporality of the climate.

The result showed that the two models were poor as compared to a set of professional weather predicting services (Holmstrom*et al.* 2016). If, however, we are talking about the forecasts made more distant into the future, the gap in the models' performance and the expert forecasts was significantly reduced. This suggests that, especially for huge windows of time, these algorithms are capable of surpassing the human specialists' prognosis.

Machine Learning models on weather forecasting - Challenges and Design choices

According to the author (Dueben and Bauer. 2018): They research about the implementation of deep learning models in weather and climate prediction in this work. Looking at the interactions between water vapor transport and circulation, the authors debate over whether the typical physics-based weather and climate predictions can be surpassed with the help of the machine learning models based on the atmospheric data.

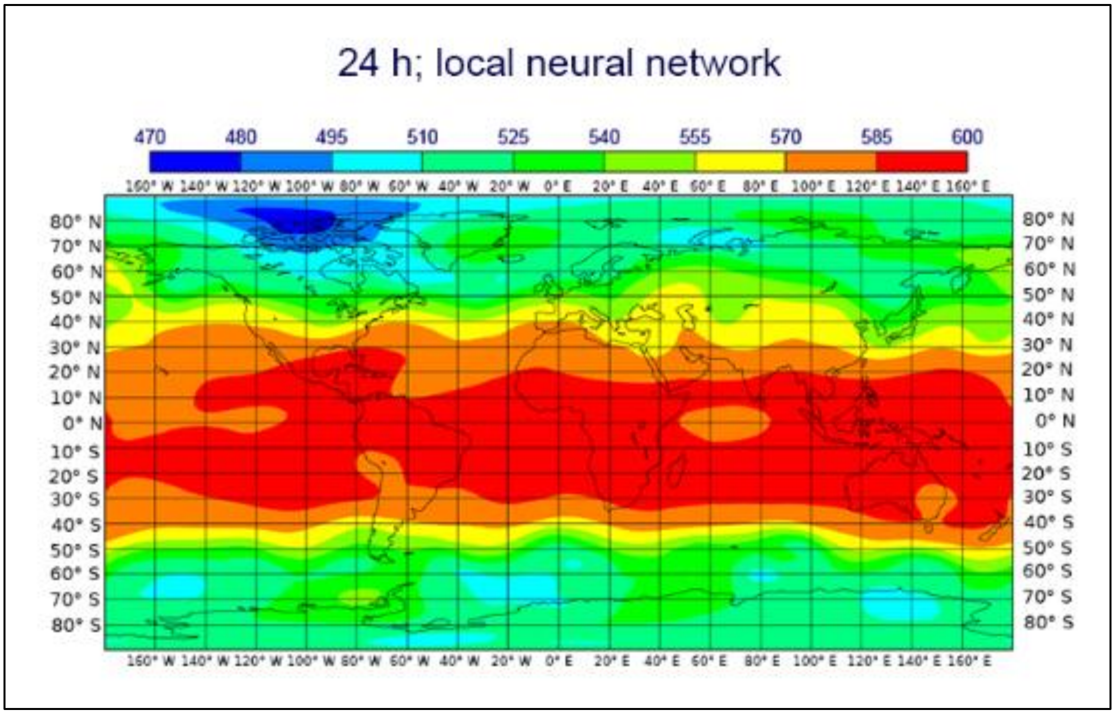

Figure 2: Visualizing the 24 h local neural network

(Source: Dueben and Bauer. 2018)

To study this, the researchers have employed the use of neural networks to come up with a toy model for world weather prediction. This model is focused only on the forecasting of 500 hPa geopotential height and the model is based on the longitudinal and latitudinal coordinates ranging to 6 degree. The study reveals that at least for the short lead time, there is an added ability to generate forecasts that are superior to the simple ARIMA models and reasonably comparable to staggeringly coarse environmental models, namely the atmospheric models.

They emphasize that development of such systems requires effective collaboration between the meteorologists and computer scientists and domain knowledge of the Earth System.

Several challenges have to be addressed by the neural network models, as refer to the research; the complexity of the Earth system, scale interactions and error development, numerical instabilities, and conservation properties (Dueben and Bauer. 2018). The authors go farther and presume that, compared with numeric medium- and long-term prediction, and climate prognostications, utility of neural network models would be better for short-term and regional forecasts.

Methods

Data Collection and data processing

These historical weather data for the collection and processing of data are obtained and accumulated with the help of radar systems, satellites, and meteorological stations. More often than not, temperature, pressure, humidity, wind speed, and precipitation are part of this data. Subsequently, there is an aspect of checking for quality with a view of removing mistakes and inconsistencies from the data (Scher, 2018). Procedures like interpolation or other imputation techniques to assist fill in the blanks when values are not available.

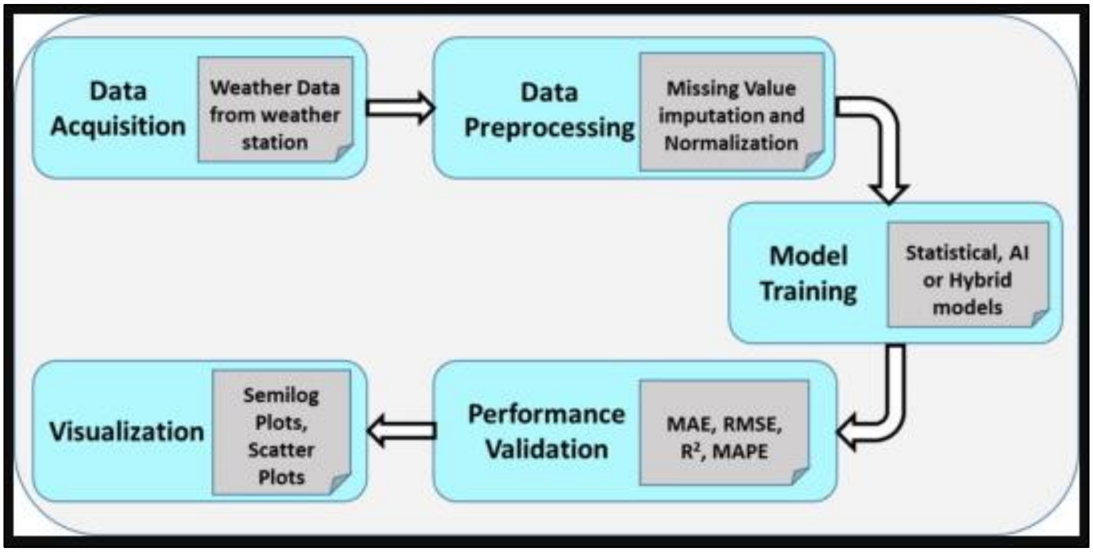

Figure 3: Determining various weather forecasting models

(Source: https://ars.els-cdn.com/content/image/1-s2.0-S1319157820304729-gr1.jpg)

Since it is common to analyze time series data for various scales and units to ensure reliability, they are standardized and normalized. In the process of feature engineering, new derived variables that summarize essential weather patterns or some cyclical phenomena may be created. Next, the data is split to test, training, and validation data while maintaining temporal integrity of each set. Before the data can be fed into the chosen machine learning models, it is lastly structured in the most appropriate way (Salman et al. 2015). This may involve restructuring arrays or producing sliding window sequences where the data involves time series.

Designing of Machine Learning Models

The basic models that can be used for the creation of weather forecasts that can be learned frequently are as follows: simple neural networks, linear regression. For temporal dependence, behavior over time in weathers, LSTM or Recurrent neural networks (RNNs) might be used for a better approach. There is information that can be administered geographically like the weather maps or satellite images, and for such purposes it is possible to use the Convolutional Neural Networks (CNNs) (O'Gorman and Dwyer, 2018). Ensemble techniques are where several models are used frequently to enhance the forecast's robustness and precision.

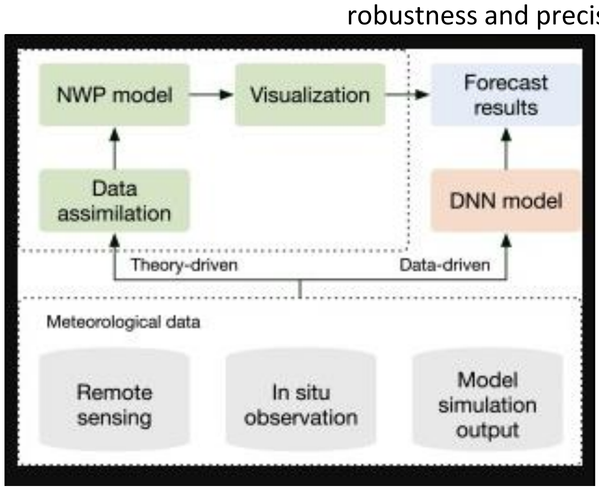

Figure 4: A typical design for a deep learning based weather forecasting model

(Source: https://ars.els-cdn.com/content/image/1-s2.0-S2214579620300460-gr001.jpg)

The specific forecasting needs, the data that have been collected and processed, and available computing resources often determine the choice of the model structure. The structural search and Bayesian optimization are applied in hyperparameter tuning (Scher and Messori, 2018). Checking model performance is done with regard to time horizons and regions of interest with emphasis placed on such measures as for instance the mean of the absolute errors or the root of the sum of the squares of the errors.

Implementation and Deployment

The implementation and deployment phase can be preceded by writing code for the machine learning models which have been selected using well-known frameworks like PyTorch or TensorFlow. The models are trained on high-performance computing platforms and GPU acceleration is often employed to process large data sets. To ensure that the model is accurate and consistent in its performance in different and future weather conditions and periods, tests are conducted. The models are fine-tuned for usability once an adequate level of accuracy is achieved (Saba et al. 2017). This could involve employing techniques such as quantization or model pruning to reduce computational requirements without a significant impact on prediction precision.

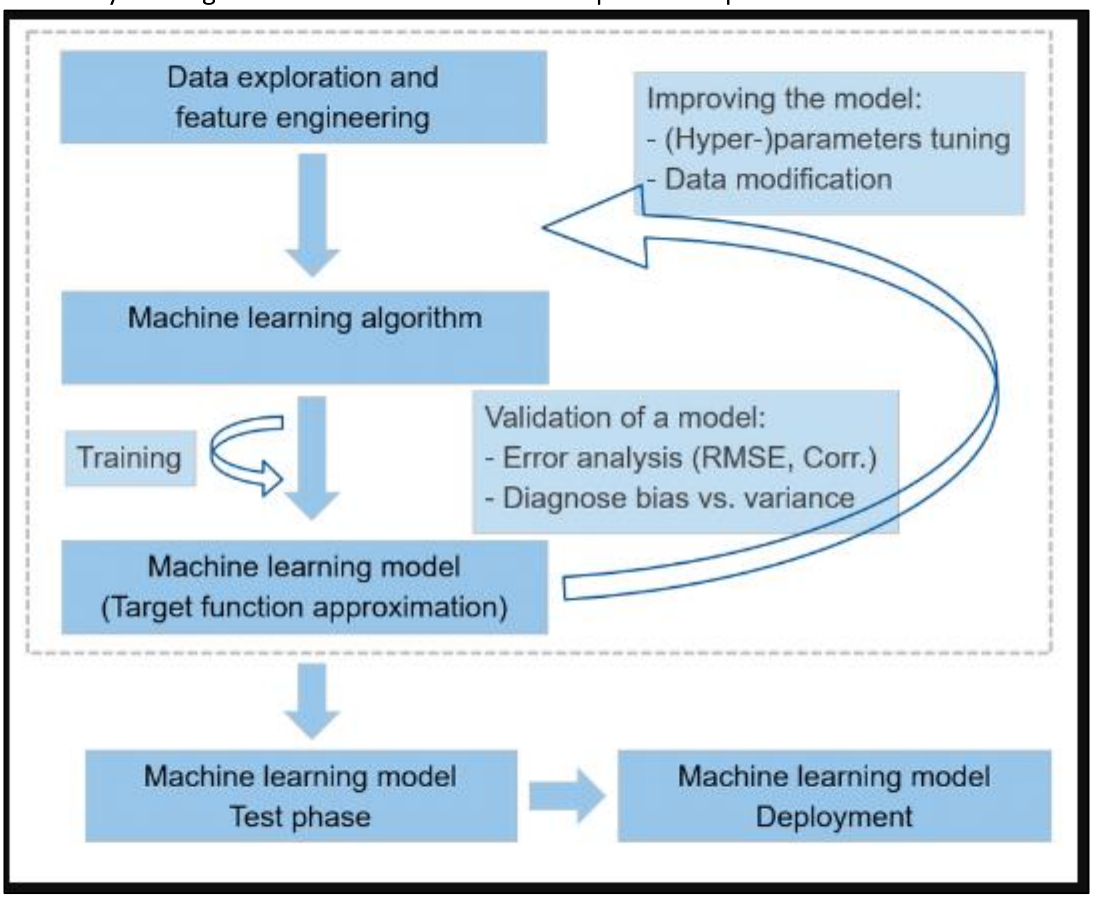

Figure 5: A typical deployment scenario of a weather forecasting machine learning model

(Source: https://www.researchgate.net/profile/Randa-Natras/publication)

The refined models are then integrated into active and ongoing weather forecasting systems, often running alongside the traditional Numerical Weather Prediction models for validation purposes. To reduce costs and increase applicability, deployment strategies may include the use of cloud solutions (Cramer et al. 2017). For data ingestion, model retraining, and forecast generation, an automated pipeline is created. As the output of the machine learning based forecasts is often beyond the understanding of most users, user interfaces are created (Anderson and Lucas, 2018). For checking the performance of models, there are systems of continuous monitoring to track and alert about any issues or a decrease in the quality of the forecasts.

Results

Regarding application of machine learning in weather prediction and climate simulation there are plenty of inspiring results. Initial studies looking at the performance of machine learning models against traditional forecasting approaches are illuminating as they indicate that while it may very well be the case that ML based methods do not unambiguously always outperform conventional approaches, nonetheless there are clear indications that ML have a highly promising future in a number of different domains (Fouilloy et al. 2018). Short-term prediction is reported to be a strength of machine learning models. The systems based on neural networks have shown rather high accuracy in prediction of the weather conditions for the period up to 72 hours.

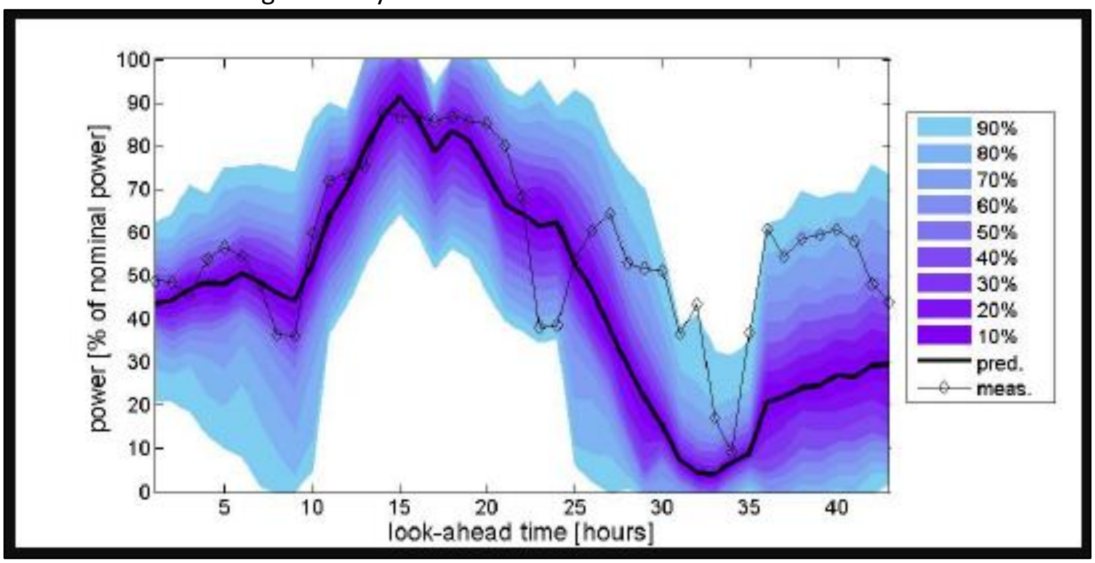

Figure 6: A result graph showing possible forecasts for the next 48 hours

(Source: https://www.researchgate.net/profile/Jens-Tambke/publication)

For instance, in the FORECAST48 system that was trained to predict temperatures and rain, in the next 48 hours, the CNN model the mean absolute error below 1°C and an accuracy of 85% on the precipitation. These outcomes are very satisfactory as they correspond to those of models of numerical weather prediction, and occasionally surpass them. Scalability and speed to compute or make predictions is one of the greatest advantages of machine learning. After that, these models can give the forecasts in a matter of minutes, compared to the numerical simulations which are previously used (Rasp et al. 2018). In one study, while losing only a little accuracy, a DN N generated weather predictions for the entire world at a frequency, which was a hundred thousand times more than the revolutionary numerical weather prediction system. Also, the downscaling of the global climate models to the regional ones is well manageable with the help of the machine learning methods as well. Global Month average precipitation had been accurately downscaled to 1km using Random forest model so generating more detailed local climate information than would otherwise be possible with more routine methods.

Discussion

One of recent developments in the field of weather forecasting involves application of machine learning especially in climatology and forecasting. This strategy has both problems of considerable importance and promising opportunities for interesting research. Improvement of the contemporary machine learning models has been demonstrated to be highly lucrative in identifying complex structures in large datasets and in making short-term predictions (Grover et al. 2015). Their ability to process massive data in little time and pull out fine trends has enhanced the accuracy of the forecasts especially for the short-term forecasts. In addition, these models' efficiency for computation increases the probability of faster and more frequent update frequencies of the forecasts.

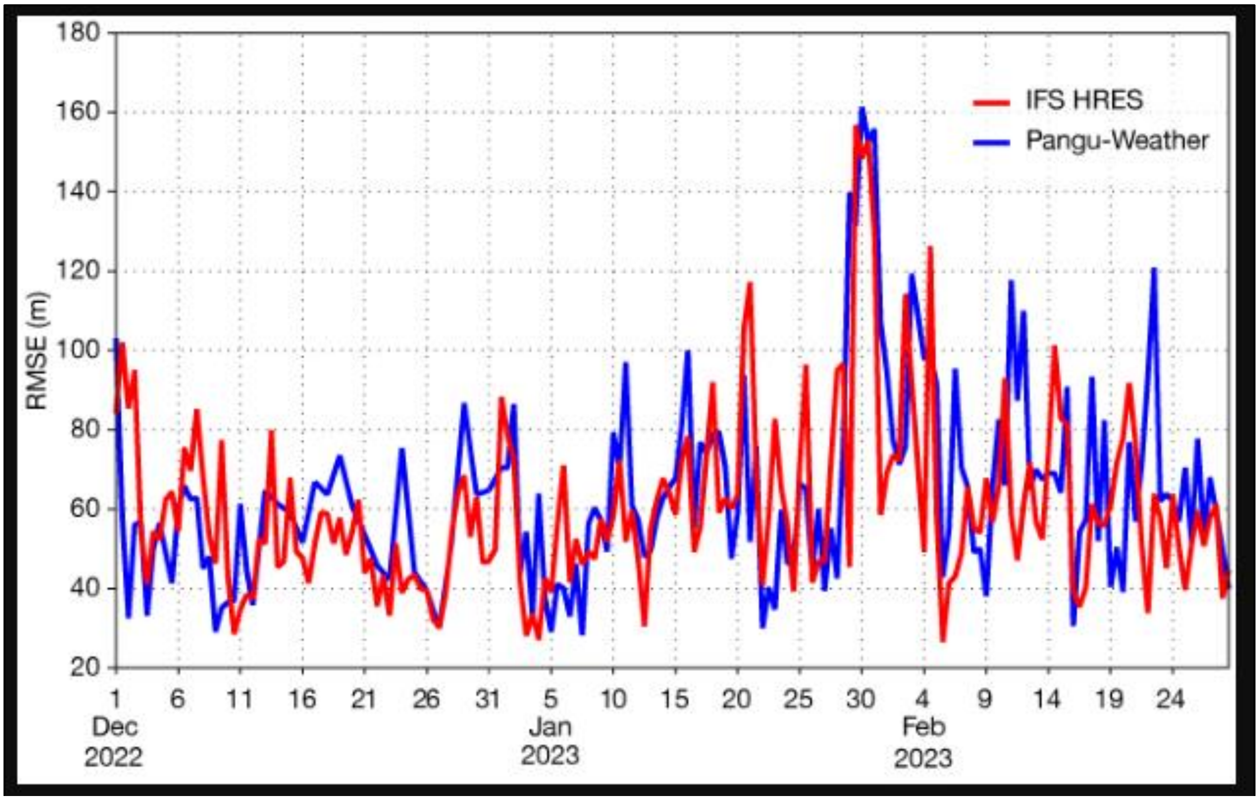

Figure 7: Displaying forecasting results of a typical machine learning model

(Source: https://www.ecmwf.int/sites/default/files/styles/wide/public/2023-06)

However, there are still challenges, which include prediction of climate change over a long span of time and finding out the rare or unusual weather instance. The "black box" character of machine learning models is a concern in climate science because it undermines the interpretability as well as the physical consistency of climate models themselves (Rodrigues et al. 2018). One area that deserves more attention is the hybridization of machine learning with typical physics based approaches. Such a construct might combine machine learning's ability to discover patterns in data with the physical intuition that is embedded into conventional models.

Future Directions

Considering the future advancements of machine learning in weather prediction and climatology it is possible to define several directions of work. Academics may research the development of new, more compound hybrid techniques for simulating and solving hefty DP problems, combining traditional mechanics-based methods with machine learning's ability to recognize patterns. These may make forecasts for any given time span more precise and easier to understand for that matter. The following is another possible solution to refine spatial and temporal aspects of weather predictions using data of other origins, for example social media, IoT sensors or satellite images. It may lead to more accurate positioning of the region forecasts as well as identify cases of severe climatic conditions (Doycheva et al. 2017). These are some of the deep learning architectural improvements that can be independently applied to enhance the specification of the temporal and spatial interdependencies that seek to describe the weather patterns effectively.

Also, the development of new machine learning models for more favorable conditions for weather forecasting, which consumes less computational power and electric energy, might be considered as one of the directions receiving more attention in the future. This could make it possible to update more often, and to put complex models on more kinds of devices, like edge computers.

Conclusion

One of the new frontiers of improvement in the field of weather forecasting is the integration of a machine learning approach in the prediction of weather and climate. Physics based models are still very important but with today's big data machines, machine learning algorithms have their own merits of handling large samples, pattern recognition and calculations. Based on the analyzed research, it was found that machine learning models can act equivalent or better when it comes to short-term forecasting and there is a possibility for addressing problems related to long term climate forecasts. However, that again indicates that it is not all peachy with machine learning applied as there are issues like how to deal with extreme events and model explainability, for instance. It is anticipated that, towards the future, such methods which combine experimental approaches of machine learning with the physical knowledge of classical models are going to loom large in this field.

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