Review of the Development of Machine Learning Application in Tropical Cyclone Prediction

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Abstract: Nowadays, along with the trend that more and more devastating tropical cyclones are happening all over the world, people's are facing serious threat. Since traditional models have trouble giving more accurate prediction results, ML models are introduced to provide a more effective way. This overview briefly summarizes the history of ML and the causes of TCs, giving some algorithms of ML that were applied to TC prediction. It also included two actual examples of ML methods that had made a success on predicting TCs. Despite the fact that challenges exist in data quality and computational resources, machine learning models have proven to have huge potential in improving the accuracy and efficiency of tropical cyclone predictions. What's more, this overview provides some possible prospects of the field, too, including model optimization, risk assessment, and interdisciplinary collaboration. These urgently-needed advancements are essential for improving the resilience of coastal rigions abilities to deal with TCs and the disaster caused by it.

Keywords: Machine learning, Tropical cyclone, Prediction, Algorithms.

1. Introduction

These days, machine learning (ML) is developing at an ever-increasing rate, which is advantageous for many facets of our life. Predicting tropical cyclones (TCs) is one important use of machine learning (ML). As everyone is aware, TCs are among the most frequent weather phenomena, and when they cause a tragedy, they have a profound effect on people's lives. One such event was in 2023, a notable instance occurred when a single TC in Malawi led to 1,209 deaths, while another cyclone in India impacted 4.4 million individuals [1]. Therefore, it is necessary to find some methods to prevent TCs from causing harm to people. Although there has been progress in recent years in predicting TC tracks, there continue to be certain issues with long-term track forecasting, where machine learning is essential [2]. Major ML algorithms used in prediction can be divided into several categories through their applications: feature selection, clustering, and regression or classification. The function of the first one is decreasing irrelevant to increase effectiveness, while the second algorithms produce a marked effect by divide sample dataset into different categories. The last method is also effective since it can deal with more complex applications [3]. Despite the fact that it is still difficult to figure out the uncertainty in forecasting the TCs, the prospect is promising by virtue of the rapid development of ML. In this article, we will talk about the history and development of ML and the features of TCs, providing a review about how people use ML methods to predict TCs. Some examples of the practical application and the future trends of the application will also be included.

2. Review of the development of Machine learning

2.1. The history of Machine learning

The earliest concept of ML dates back to the 1950s, proposed by Alan Turing who is one of the greatest pioneers of computer science. Later, in the 1950s and 1960s, some ML algorithms were invented. for example, Frank Rosenblatt developed the perceptron algorithm in 1957, which is known as the earliest artificial neural network. Also, it is in this period that the concept of ML was first officially proposed at the Dartmouth Conference. However, "everything is going smoothly" is not appropriate when it comes to the development of ML, since its development encountered two times "AI Winter".

The first time occurred in the 1970s, because the expectation is too high, but the actual development is slow, making the financial support eliminated sharply. Luckily, in the 1980s, thanks to the development of the backpropagation algorithm, which allowed the neural networks to be more efficient, ML obtained opportunities to advance again. But in 1987, the second "AI Winter" happened because of the decline in the demand for AI hardware, which blocked ML development. Fortunately, due to the introduction of new algorithms and improvement of computers' hardware, ML is becoming more and more important today and has gained lots of achievements. For example, Big Blue, an AI developed by IBM, beat world chess champion in 1997, which was benefited by the development of ML [4].

2.2. The concept of Machine learning

ML is a process where a system can learn from experience, and the key lies in creating computer programs that can learn independently. Over the years, numerous ML methods have been developed. Supervised learning, the most commonly used type, involves algorithms receiving labeled datasets for training, with the expectation of predicting unseen data based on what has been learned from the labeled data. Unsupervised learning, on the other hand, deals with unlabeled datasets, aiming to discover specific patterns or structures in the data and is widely applied in clustering and association. Reinforcement learning enables algorithms to interact with the environment, receiving rewards or penalties to learn decision-making, being effective in areas such as robot control and games. Deep learning, originating from the concept of artificial neural networks, can learn hierarchical features and patterns and has now expanded its application to various fields, including image recognition and natural language processing [5].

In the field of predicting tropical cyclones, supervised learning and deep learning are the most common methods. It is obvious why supervised is so useful here, since it can use a labeled dataset to train the models. It means that after receiving enough datasets, the specific model will be able to give some correct feedback about the intensity and trend of tropical cyclones. Deep learning, especially the convolutional neural networks(CNNs), plays a significant role in the prediction because it has the ability to explore the complex and sometimes confusing patterns of tropical cyclones by extracting specific features from satellite imagery. This paper will explore these algorithms in greater depth later.

3. Overview of the tropical cyclone

3.1. The causes of tropical cyclone

According to the definition in the World Meteorological Organization(2017) Global Guide to Tropical Cyclone Forecasting, the origin of TCs can be described as the development from a tropical disturbance, a compact, organized storm system in the tropics or subtropics, to a tropical depression or tropical storm. A large-scale tropical storm with a warm center and organized thunderstorms around a defined core [6]. When it comes to the factors that can affect the size and density of TCs, complex thermodynamic, including sea surface and air temperature, moisture, and convection, are involved. What's more, dynamic interaction between the ocean and atmosphere also plays a vital role in forming TCs [7]. To predict TCs more effectively, they must figure out the mechanisms of TCs. It always starts with atmospheric disturbance above the tropics. Under suitable temperature and conditions, these disturbances will form a more coherent circulation system. With the rising moisture later condensing, the storm will be strengthened, gradually becoming a low-pressure center, which is able to make the surrounding air converge and rise. In favorable atmospheric conditions, this system will be intensified, finally developing into TCs.

3.2. Current frequency and trends of tropical cyclone

Since 1980, the frequency of tropical cyclones (TCs) has been continuously on the rise, particularly in the number of intense cyclones. However, the Accumulated Cyclone Energy(ACE) index has not exhibited an obvious upward trend. Regionally, the Northwest and Northeast Pacific regions witness the highest TC frequencies. In addition, the formation and intensity fluctuations of tropical cyclones are intricately linked to oceanic driving factors. These include the ENSO (through the Ni ñ o 3.4 index), Southern Oscillation Index (SOI), and Pacific Interdecadal Oscillation (IPO) index. These changes are in harmony with the variations in the number of tropical cyclone years in the interannual cycle of 3-7 years and the decadal cycle of 10-13 years [8]. On the other hand, global warming has a great impact on the TCs, considering it allows favorable atmospheric conditions to happen earlier so it may advance the seasonality of TCs, which might make a greater impact on people's lives.

4. Application of machine learning in tropical cyclones prediction

The first attempt at using ML to predict TCs is in the 1990s. A paper discussing TCs identification and tracking that used neural technology marked the first ML application in TCs prediction. Up to now the development of this kind of application has made a big progress, since we have ranges of methods to create models to predict TCs. The most common ML methods used to predict TCs is long short-term memory(LSTM) and convolutional neural network(CNN). LSTM is a kind of recurrent neural network(RNN) that is able to capture long-term dependencies in time series data. When forecasting TCs, LSTM is widely used since it has great ability to remember as well as deal with sequential data. It is crucial in prediction due to it being able to predict the track of TCs [9]. On the other aspect, the role of CNN is also significant. It is a deep learning model that is good at processing image data [10]. As you can imagine, today this paper have lots of satellites to keep track of TCs and make predictions with these devices, but how do computers deal with this imagery data. Actually, this is the function of CNN. It is able to extract specific features from the satellite imagery and give the structure and intensity of TCs. Using convolutional layers, pooling layers, and fully connected layers, CNN can learn to identify the patterns of TCs automatically. There are also some other useful methods and algorithms in predicting TCs, such as Support vector machines(SVM), Random forest(RF) and Decision trees(DT) etc.

5. Actual case analysis

In the past, the most common methods people used in predicting TCs were statistical forecasting models and numerical prediction models, which required high computational capability of computers, and it was such a costly method. On the other hand, it also has relatively high low prediction accuracy. For instance, as reported by the Shanghai Typhoon Institute, there were prediction errors of about 97.4 kilometers, 188.2 kilometers, and 302.7 kilometers in the tracking of typhoons within the respective early, intermediate, and extended 24-hour, 48-hour, and 72-hour time frames when using a numerical forecasting model [11].

Consequently, a more effective method is necessary to be invented. Let's look at a novel method using an Artificial Neural Network(ANN) as an example. In 2019, some researchers tried to train the ANN model to simulate the storm tide and the extent of onshore flooding, and the case they focused on is the 1999 Odisha Super Cyclone, a tropical cyclone that resulted in a lot of casualties, with estimates ranging from 10,000 to 20,000 deaths. The researchers used pre-computed data of storm tide and inundation for training, the model achieved a 99% success rate for the entire Odisha coast. What's more, the ANN model demonstrated rapid computational times for predicting storm surge and inundation, which were completed in just seconds, compared to traditional models. Verified based on archived records of storm surge and inundation, with accuracy rates of 92% and 94%, respectively. The study confirms the efficacy and potential real-time application of the ANN model for disaster risk reduction during tropical cyclone events, proving that ML is actually a helpful tool to predict TCs [12].

Another instance is using a deep learning method based on an autoencoder (AE) and gated recurrent unit (GRU) for predicting the path of tropical cyclones. The general process of the method is separated into three steps. The first step is data preparation, meaning that the related data need to be format unified and then suitable for calculations. Secondly, an auto-encoder (AE) will be used to find significant features from the processed data, eliminating the complexity of the data. The extracted features will be sent to the next step, predicting path. In this step, researchers utilize the gated recurrent unit (GRU) to analyze the data with chronological order based on the previously extracted features and then predict the future path of the tropical cyclone. Some TCs, including Meranti, Haiyan, Tip, and Dujuan, were used as the data to examine the model. The data were input into the trained AE-GRU model to predict the coordinate sequence of the path in the next 72 hours. The result of the model achieved such great success in predicting TCs, with predicted tracks that were close to real tracks [11].

6. Future development direction

Despite the fact that ML has played a vital role in predicting tropical cyclones (TCs), there are still numerous aspects that have room for improvement and further exploration. Firstly, model optimization remains a crucial area. As the cornerstone of ML, an enhanced model not only boosts the accuracy of TC predictions but also empowers computers to handle more complex and unpredictable TC behaviors that often defy common sense. This could involve refining algorithms, improving data processing techniques, and enhancing the model's ability to adapt to changing TC patterns. Secondly, risk assessment and disaster management in the context of TC prediction are of utmost importance. Given that TCs can trigger a cascade of disasters such as floods, storm surges, landslides, and mudslides, having a comprehensive pre-assessment and efficient disaster management strategies in place can significantly mitigate property damage and reduce personnel casualties. This may include developing advanced warning systems, improving evacuation plans, and enhancing emergency response capabilities. Thirdly, interdisciplinary collaboration holds great promise. Although ML has achieved notable success in TC prediction, integrating it with other disciplines is essential. Collaborations between meteorologists, data scientists, and experts from diverse fields such as hydrology, geology, and social sciences will foster the creation of more effective ML methods. For instance, combining meteorological data with geographical and social factors can provide a more holistic understanding of TC impacts and lead to more accurate predictions. By focusing on these key directions, the field of TC prediction using ML can continue to evolve and better serve society in the face of the ever-present threat of tropical cyclones.

7. Conclusion

This paper is an overview of the development of ML in predicting TCs. We briefly review the history and basic concept of ML to help readers understand the important meaning of ML to people's lives as well as the cause and development trends of TCS. After that, we explore some common ML algorithms and methods used in predicting TCs, including LSTM, CNN, etc. Then it's the part of some actual instance, where we choose two places as the examples. Compared to the past methods, statistical forecasting models and numerical prediction models, these two methods improve accuracy as well as efficiency. The first example focuses on the 1999 Odisha Super Cyclone, one of the most devastating tropical cyclones. With the trained ANN model, researchers make a success in predicting storm surge and inundation. On the other hand, another example used deep learning methods based on AE and GRU, which help people improve the prediction of TCs track a lot. The final part is concentrating on some future direction. In a word, the application of machine learning methods in tropical cyclone prediction has shown promising prospects in enhancing the accuracy and efficiency of forecasting models. The future of this field, however, still faces a range of challenges, from depending on quality training data too much to the high computational intensity that some models need. In addition, the transferability of the model between different cyclonic basins remains an unresolved issue, highlighting the need for tailored approaches. Consequently, future research should focus on how to address these limitations and develop more adaptive machine learning frameworks and models.

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