Creating Interpretable Data-Driven Approaches for Tropical Cyclones Forecasting

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Abstract

Tropical cyclones (TC) are extreme weather phenomena that bring heavy disasters to humans. Existing forecasting techniques contain computationally intensive dynamical models and statistical methods with complex inputs, both of which have bottlenecks in intensity forecasting, and we aim to create data-driven methods to break this forecasting bottleneck. The research goal of my PhD topic is to introduce novel methods to provide accurate and trustworthy forecasting of TC by developing interpretable machine learning models to analyze the characteristics of TC from multiple sources of data such as satellite remote sensing and observations.

Introduction

Over the past 50 years, TC have caused 1942 disasters, resulting in 779,324 deaths and $140.76 billion in economic losses(WMO 2021). However, there are forecast bottlenecks in existing forecasting methods; for example, while TC path forecasting has made tremendous progress over several decades, intensity prediction from numerical models and statistical schemes, especially for TC rapid intensification(RI), has been a daunting challenge, and the interaction of insufficient resolution of scales and models has led to slow improvement in TC forecasting (Cangialosi et al. 2020). Our main focus is to use deep learning models to bridge this gap, but deep neural networks are considered a highly accurate model, but they are considered black box and TC forecasting is a high risk problem affecting the productive life of a large population, so its direct modeling of this problem is not recommended. We try to combine ML and interpretable to make more accurate and credible forecasts for TC, where interpretable is consistent with meteorological principles and meets the practical needs of forecasters. Two key issues facing our current research can thus be summarized.

How to obtain sufficiently high forecast accuracy based on machine learning to break the forecast bottleneck of traditional forecasting methods for TC?

Machine learning methods have been shown to have great potential in the field of meteorological and ocean forecasting. Long-term forecasts using convolutional neural networks in ENSO outperform all numerical models and break the spring forecast bottleneck of ENSO forecasts(Ham, Kim, and Luo 2019). For TC forecasting, machine learning should be applied to satellite observations for TC rapid intensification forecasts, exceeding the RI consensus of the National Hurricane Center(Su et al. 2020), indicating the strong potential of using ML applied to TC operational forecasting, and we expect to further investigate ML for TC intensity and RI forecasts in multi-source data.

How to solve the black box problem of machine learning-based TC forecasting based on interpretable methods?

The complexity of the ocean and atmospheric environment makes it challenging to design interpretable models , and there are gradually some researches in the field to address the challenge, for example, McGovern et al. summarize the model interpretation and visualization (MIV) methods of multiple ML models in meteorology(McGovern et al. 2019), which can enable meteorologists to understand what ML has learned, while the trade-off between interpretability and accuracy is also an important topic.

Current Progress

In the first two years of my PhD, I conducted some basic research for TC forecasting with a wide coverage.

Automatic detection of TC is the fundamental for further research on TC, I attempts to perform automatic identification of TC in global numerical models using a two-branch convolutional neural network, and we also employed generative adversarial networks and transfer learning for automatic detection of TC in small sample infrared images(Pang et al. 2021).

Accurate estimation of TC characteristics such as structure and intensity is key to TC forecasting, so I employ convolutional neural networks to objectively estimate the dimensions of TC in images from infrared satellite images, and the results indicate that the method exceeds existing operationally-run TC structure estimation models; I devolop a high-dimensional tensor ARIMA model for TC intensity forecasting, which In order to solve the problem of short intensity series of each TC, the high-dimensional tensor is used to obtain more relevant information, and the results are obtained well in short-term forecasting.

In addition to modeling TC directly, I also attempted to forecast the impact from TC using the ML method, which in-

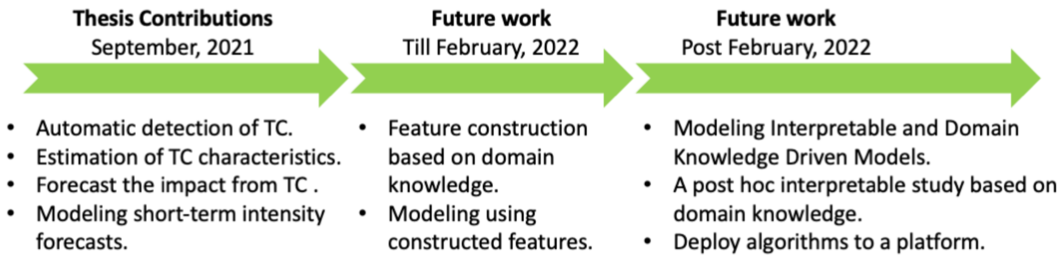

Figure 1: Brief timeline of the proposed research plan.

corporates factors such as TC intensity into the wave height prediction of TC(Meng et al. 2021). The results of modeling using bidirectional GRU show that the forecasts exceed previous studies in forecasting accuracy.

In the preliminary work, we tried to comprehensively grasp the development and impact laws of TCs, but the preliminary results seldom incorporate interpretability into the modeling, so our next phase will focus on the research of interpretable methods. Meanwhile, the preliminary work lacks the focus, and intensity and structure are the key factors of TC forecasting, and there are forecast bottlenecks in the existing operational forecasting models, so the later phase will focus on the intensity and structure characteristics of TC forecasting.

Future Work

The core step of the paper are to build physically guided machine learning models sufficient to discover rules in multi-source TC data in an interpretable way, we aim to solve the TC forecasting bottleneck and to address the ML-based TC forecasting black box problem, to achieve this goal, the paper plans to carry out the following three subtasks, an abbreviated schedule of which is given in Figure 1.

Research on feature construction based on domain knowledge. I intend to use domain knowledge of marine and atmospheric sciences to construct features that are more suitable for neural network and machine learning inputs. For example, features constructed based on empirical modal decomposition and empirical orthogonal function methods have been shown to improve forecasting performance in the field of environmental prediction, and decomposition for spatio-temporal sequences is an important topic for us. Meanwhile, I am working on factor selection based on interpretable machine learning, where XAI can rank factor importance and mine factor relationships.

Interpretable and Domain Knowledge Driven Models. Due to the modularity and flexibility of the neural network architecture, I would like to build a model with a physically guided structure. Jia et al. add Energy Fluxes to the model in the LSTM can not only improve the accuracy of the modeling but also improve the model interpretability, I am also interested in building a hybrid model of physical models and machine learning, such as residual modeling.

A post hoc interpretable study based on domain knowledge. Multiple sources of data will be used to forecast TC, so convolutional neural networks and recurrent neural networks will be involved, so I will design post hoc interpretable and visualization schemes for these two types of network architectures, which can be trained to be able to derive prediction basis and try to seek new knowledge insights in the interpretable result species, and analysis based on domain knowledge is the highlight of this thesis.

The expected contributions include the use of various domain tools to enable a transparent machine learning framework for tropical cyclone forecasting, including explainable and MIV methods, deep learning and domain knowledge inspired and guided methods. As an applied research, it is critical that the designed models work in real-world operations, and my goal is to integrate all the designed methods into a platform capable of forecasting TC in real time.

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