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Hybrid Approaches in Weather Forecasting: From Numerical Models to Deep Learning

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Abstract. This survey reviews the fundamental principles and major approaches used in modern forecasting, with a focus on numerical weather prediction (NWP) and deep learning. NWP remains the cornerstone of operational forecasting, utilizing mathematical equations of atmospheric dynamics to produce high-resolution predictions. The computational demands and strengths of physics-based methods are exemplified by representative models such as the Global Seasonal Forecast System (GloSea5) and the Weather Research and Forecasting (WRF) system. However, deep learning techniques like as convolutional architectures and distribution-based neural networks each have advantages that make them helpful for examining huge meteorological datasets with nonlinear correlations. Validation, uncertainty quantification, model interpretability, and accurate forecasting of extreme weather events remain challenges despite advancements. It is anticipated that future advancements in high-performance computing, multi-source data assimilation, and hybrid methodologies that integrate machine learning and physical modeling will increase the utility and dependability of predictions. This study summarizes recent advancements, points out unresolved issues, and suggests exciting avenues for further weather forecasting research.

Keywords: Weather forecasting, Numerical weather prediction, Deep learning

1. Introduction

Weather forecasting is a vital skill that people use to interact with nature. Forecasting technology has advanced quickly from its early days of depending on empirical observations to the use of numerical models and satellite data. The accuracy of short-term forecasts has continued to improve as computational power and observational data have increased. However, the complexity and volatility of the atmospheric system continue to make forecasting challenging. Given the rise in catastrophic weather events and the speed of climate change, more accurate and diverse forecasting methods are especially important.

Analyzing the existing conditions of the atmosphere, the sea, and the land surface is the first step in weather forecasting [1]. Accurate judgments depend on obtaining reliable observations from a variety of platforms, such as orbiting satellites, sensors, weather airborne, ground observatories, and airplanes (both crewed and off). Because prediction effectiveness depends in part on the quality of the underlying study, researchers are constantly developing techniques to incorporate data into four-dimensional model representations of the Earth system. These studies play an important role in

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weather forecasting and support scientific research to improve weather prediction methods and instruments [1].

This paper's objective is to offer a comprehensive survey of major approaches in weather forecasting, with an emphasis on numerical weather prediction and deep learning. It examines sample models, highlights the essential ideas, and contrasts their advantages and disadvantages. It also highlights important issues like uncertainty quantification, model interpretability, and verification. It also looks at new approaches like hybrid modeling and international cooperation. This study attempts to provide insights into how weather forecasting may change to meet the increasing demands of a changing world by combining these advancements.

2. Numerical Weather Prediction (NWP)

What is often referred to as a numerical prediction model is the selection of a suitable system of equations and the sequence of numerical computations to be carried out to ascertain approximate solutions for this system [2]. This fundamental tool is utilized for climate simulation as well as weather forecasting. Automating meteorological forecasts is the goal of numerical weather prediction, which entails many well-defined procedures, including data collection and control, analysis to determine the initial state of the atmosphere, forecasting the initial state at a specified range, calculating the characteristic weather parameters at the local scale, and customizing and disseminating the results [2].

2.1. Finite difference methods

Estimations of finite differences for derivatives have been used to solve differential equations since Euler's application in one dimension in 1768 and Runge's expansion to two dimensions in 1908 [3]. Finite difference approaches have been used to solve complex scientific and technological problems since the introduction of computers. The finite difference approach is founded on the approximation of derivatives by differential quotients. The computing domain is initially divided spatially, time steps are discretized, and then differential approximations are used at the spatial points and for the time step. The discrepancy between the numerical solution and the actual solution resulting from the difference approximation is termed the truncation error. The truncation mistake arises from selecting a finite number of terms from the Taylor series [3].

2.2. Weather Research and Forecasting model (WRF)

The WRF-ARW model has been used to simulate weather prediction [4]. The model was implemented between September 21 and September 25, 2019. Essentially, two types of data are employed in this study. The information comes from autonomous weather stations (AWS) and the global forecast system (GFS). The governing equations are solved on a discrete grid by the dynamical core, which ignores terms with little meaning. Utilizing a scaled description in WRF, unresolved phenomena like as radiation, cloud micro mechanics, broad and superficial cumulus conduction, precipitation, and turbulence impact the resolved scales [4].

2.3. Global Seasonal Forecast System Version 5 (GloSea5)

GloSea5 uses the Ocean Assimilation Model (FOAM) Ocean Analysis forecast to set up the ocean and sea-ice components of the connected prediction model [5]. GloSea5, a straightforward monthly to seasonal forecast system, is composed of three parts: a hindcast, a seasonal forecast, and an

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intraseasonal prediction. A 3D-Var assimilating system for ocean and sea-ice circumstances has been installed as part of GloSea5 upgrades, and the horizontal resolution in the ocean and atmosphere has been improved. From year to year, GloSea5 shows improved predictions of the primary types of variability. Forecasts of El Niño-Southern Oscillation in the Tropics are less prone to mistakes and more accurate compared to those in the West Pacific. In the Extratropic, GloSea5 shows unprecedented prediction reliability and accuracy for the Arctic and North Atlantic oscillations [6].

3. Deep learning methods

3.1. Distribution-based neural networks

Generating a probabilistic weather prediction by training a neural network to anticipate whole probability density functions for every location and time, instead of just one output value [7]. This gets around the usual problem of deducing uncertainty from neural network predictions and allows for the measurement of skill measures in addition to uncertainty. This method is data-driven, and it uses a neural network trained on processed ERA5 data from the Weather Bench dataset to predict the geographic potential and temperature three and five days in the future. Finding the most crucial input variables is the result of data exploration. Splitting these variables into smaller ones allows several neural networks to be trained, which in turn increases computing efficiency. This is the first time that a multilayered neural network has been used to mix the outputs with weather data [7].

3.2. Deep convolutional neural networks

In the Northern Hemisphere, use deep convolutional neural networks (CNNs) trained on past weather information to forecast one or two fundamental meteorological fields on a grid to build simple weather prediction models without explicit understanding of physical processes [8]. Although an operational full-physics weather prediction model is superior, CNNs trained to predict five hundred hectopascal geographical potential height perform better than long-term climate modeling, and the dynamically constructed barotropic vorticity model with forecast lead periods up to 3 days. Notably, the barotropic vorticity equation, the formula of fundamental dynamics that only employs five hundred hectopascal data, is unable to anticipate significant fluctuations in weather system intensity, but these CNNs can. Up to 14 days ahead of time, CNN can accurately predict realistic atmospheric conditions and reflect the climatology and yearly changes of 500 hectopascal heights [8].

4. Challenges

Verification and assessment of weather forecasts provide major issues for operational agencies [9]. Operational personnel from six different nations participated in a series of online training and surveys that looked into these issues. Five major themes emerged: inadequate verification methods for new as well as existing products; inadequate, along with unclear data collection; challenges with precisely describing people's daily lives with reduced measurements; inadequate forecasting and comprehension of intricate authentication data; and institutional factors such as limited resources, changing responsibilities for meteorologists, and concerns about reputational damage [9].

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5. Future directions

We are unable to measure what we still don't know about meteorology [10]. New discoveries are frequently discovered in meteorology, which broadens our knowledge while also emphasizing the fact that there is constantly more to discover. We can improve long-term projections, alerts, predictions, and worldwide readiness and reaction to all kinds of weather events. Weather forecasting is a rapidly developing field that will require a global strategy to grow and reach the general public, even while advancements are made in particular countries [10].

6. Conclusion

With the shift from conventional empirical techniques to numerical and data-driven models, weather forecasting has advanced significantly. The foundation of operational forecasting remains Numerical Weather Prediction (NWP), which offers dependable findings based on physical principles but faces obstacles, including computing complexity and long-term predictability limitations. Although they frequently have interpretability and generalization issues, deep learning approaches have opened up new possibilities by providing adaptable, data-centric models that capture intricate weather patterns. Uncertainty in data collection, the difficulty of validating predictions, and the accurate prediction of severe occurrences under climate change are just a few of the urgent issues facing the discipline today. With the help of advancements in supercomputing, high-resolution data, and international cooperation, hybrid systems that combine physical and data-driven models are probably going to lead to future breakthroughs. Ultimately, producing projections that are not merely more accurate but also more useful to society will depend on the integration of many methodologies. Future advances are likely to come from hybrid systems that mix physical and data-driven models, aided by developments in supercomputing, high-resolution data, and global cooperation. Finally, producing projections that are not only more accurate but also more useful to society will depend on the integration of many methodologies.

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