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A Study on Quantum Machine Learning for Accurate and Efficient Weather Prediction

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***Abstract*—Recently Quantum Computing has gained much attention in the field of data science and computational problem solving. It is expected that the quantum machine learning will help researchers to find solutions for many complex problems in areas such as weather forecasting, data science, computational biology, energy management, secure communication, and many others. This paper presents a study on quantum machine learning techniques, challenges and applications of these techniques in climate change prediction, and weather forecasting towards future research in Quantum Machine Learning and Quantum Computing. It also discusses the latest developments and trends in Quantum machine Learning and presents practical examples to understand how Quantum Machine Learning considerably improves the performances of existing machine learning approaches.**

Keywords—Quantum computing, Quantum machine learning, Weather prediction, Climate prediction, Data science

I. INTRODUCTION

Quantum computing basically works on the basis of two principles of Quantum mechanics. The first principle is superposition. It states that the quantum states can be added together and the qubits can be broken down into multiple quantum states. This principle allows the bit to be both one and zero or neither at any given time. The Qubit representation is illustrated in Fig. 1.

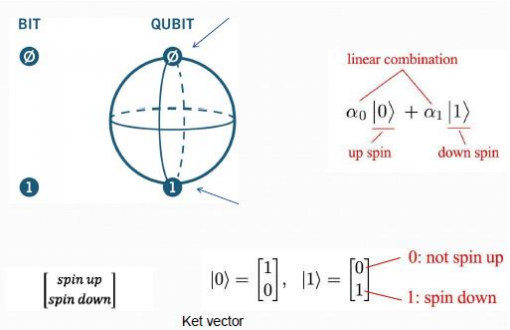

Fig. 1. Qubits representation

Utilizing this property, one can use qubit to store and process information much faster than classical computers. The second property called entanglement connects two qubits together wherein when one qubit is altered, it will change the other. This property plays an important role in applications such as malicious attack detection, secure communication, and information processing. Interestingly, the qubits can be used to train machine learning algorithms in a much faster way.

The Quantum Machine Learning allows us to train larger and more complex models more efficiently. In quantum computing, the qubits can be turned into bits and vice versa. The major challenge in the quantum device development is that the qubits will lose quantum properties due to de-coherence. This means that qubits will become classical bits when these are in superposition state. This problem may occur in mid-training which produces errors while trying to compute specific values. Naturally, environmental factors would cause noisy intermediate states that disturb the quantum devices [1]. De-coherence can be addressed by protecting qubits from vibrations or by keeping them extremely cold. Many researchers are trying to find approaches to address this research challenge by developing error correction mechanisms. In this perspective, the quantum machine learning is capable of mapping complex weather patterns. Fig. 2 shows quantum machine learning based applications and optimization techniques.

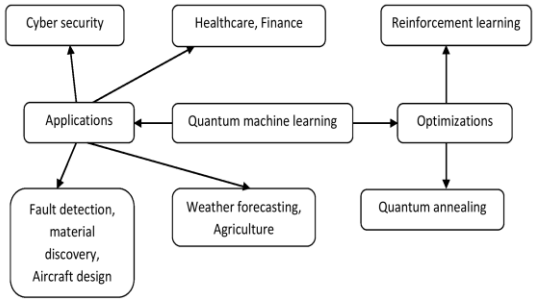

Fig. 2. Quantum machine learning based software components

Since the high-performance computers require high energy, the consumption rates of those machines are not sustainable and also they produce huge amounts of CO_2 while running data-intensive applications [2]. Therefore, an alternate option to deal with this problem is to use more powerful quantum computing technologies which require lower energy. Quantum computers follow principles of quantum mechanics to perform computationally complex tasks in less amount of time. Some of the applications of quantum computing are as follows.

Weather predictions: Quantum computing is capable of limiting or avoiding carbon emissions. This enables the development of more accurate climate prediction models that help scientists in understanding climate changes. [3]

Material development: The optimization in material design, efficient and cost-effective utilization of energy will have major impacts on climate change. Quantum computing

can help scientists in developing more efficient and accurate simulation models for analyzing interactions among more complex molecules[3].

Sustainable Agriculture: The production process followed in fertilizer development requires 2% of global energy [3]. Quantum computing gives a motivation to develop environment-friendly fertilizers by simulating the behaviour of bacteria, proteins, and enzymes.

Electric vehicle development: the main focus is on increasing of energy density. In addition, the simulation models could help in analyzing chemical reactions when materials interact with chemical catalysts[3].

Aircraft design: It is expected that the Quantum computing based design solutions will be useful to reduce wind drag and CO_2 emissions, and to develop more energy efficient aircraft[3].

Some of the research questions and answers are presented in Table I.

TABLE I. RESEARCH QUESTIONS AND ANSWERS

S.No.	Questions	Answers
1.	How to achieve accurate climate change prediction?	Effective extraction of data and filling the missing values quickly will help in achieving accurate climate change prediction.
2.	How to provide parallel computation?	As part of the quantum process, all coefficients can be modified in the superposition to provide parallel computation. For developing the quantum memory and processors, the qubits need to be transformed to the coherent state while performing entanglement.
3.	How the quantum computer has exponential computing power?	Quantum computer uses qubits (quantum register) which can describe 2^n base states for the given 'n' qubits and this can have infinite number of states to represent the superposition of the base state. The computing operation involves rotation of the state vector in the quantum state space.
4.	In what way quantum machine learning will greatly reduce the impact of the weather on renewable energy?	Quantum machine learning will utilize the computational power of qubits and quantum-inspired optimization, for efficiently tracking and predicting meteorological conditions by analyzing big data that contains many variables. This will provide a better way to control resources and to take care of the variations occurring in the weather dependant renewable energy generation.
5.	What are the computational problems solved by Quantum computing?	Shor's algorithm tried to solve the NP-hard problem, i.e., factoring large numbers in encryption. Recently, Tail Assignment Problem solved the logistic problem in the aviation industry. It aimed to assign routes to flights by minimizing time taken for maintenance. The research team at Chalmers University of Technology has executed the Quantum Approximate Optimization Algorithm (QAOA) on a processor by utilizing two qubits.
6.	Discuss on the open challenges related to the Quantum machine learning.	Quantum machine learning should be able to model large multi-dimensional spaces in a much better way. It has been proven that the HHL (Harrow, Hassidim, Lloyd) algorithm can solve linear systems of equations exponentially faster. As the complexity of linear system increases, it requires more number of qubits. As of today, only a limited number of qubits are available. Other challenges include coherence time handling, measuring qubit fidelity, and solving connectivity issues.
7.	Discuss few words on "principles of quantum mechanics".	Principles of Quantum mechanics are being introduced to tackle problems by formulating a new theoretical framework (Paul Dirac, 1930). Some of the principles are principle of superposition, principle of entanglement, principle of uncertainty, and Hamilton's principle.

The rest of the paper is organized as follows. Section 2 presents a concise overview of existing quantum machine learning approaches and their applications related to Quantum Machine Learning for weather forecasting and climate analysis. Section 3 starts with future directions and ends up with conclusion.

II. QUANTUM MACHINE LEARNING FOR WEATHER PREDICTION-A REVIEW, PRACTICAL EXAMPLES

Recently, the uses of quantum computing and quantum machine learning have increased rapidly in many fields. Some of the literature discussed that quantum methods will provide a way to reduce the computational complexity, increase the speed of computation enormously, provide precision weather forecasts, and will help to achieve accurate climate change prediction. In the variational weather prediction methods, the operational systems at global-scale and regional-scale require high computational resources and huge memory [4]. To deal with this issue, quantum computing technique will be applied for solving the computationally complex problems. Unlike classical computers, quantum computer uses qubits (quantum register) which can describe 2^n base states for the given 'n' qubits and this can have infinite number of states to represent the superposition of the base state. The computing operation involves rotation of the state vector in the quantum state space.

As part of the quantum process, all coefficients can be modified in the superposition to provide parallel computation. For developing the quantum memory and processors, the qubits need to be transformed to the coherent state while performing entanglement. But, the qubits may get affected by noise or power fluctuations in the system. Hence, the development of general purpose quantum computing device still requires technological intervention. Recently, taxonomy is developed for quantum computing and it is observed that there is a tremendous progress in the development of hardware and software tools/technologies in the field of quantum computing [5]. Table II shows software tools and technologies and the programming languages used for developing solutions.

TABLE II. SOFTWARE TOOLS AND TECHNOLOGIES IN QUANTUM MACHINE LEARNING BASED DEVELOPMENT

Tools/Softwares	Programming languages used
Quantum Programming Studio [6]	Javascript
Quantum Circuit [7]	Javascript
Jsquis [8]	Javascript
Qiskit [9]	Python
Quantum Development Kit (QDK)[10]	Python, Q#

The review in the present study analyzes limitations in existing weather forecasting models to understand how quantum machine learning can outperform other classical methods by providing efficient solutions. Since the values of weather variables (e.g. air temperature, humidity, and atmospheric pressure) are dynamically changing due to unexpected events, accurate prediction is difficult to achieve. In certain situations, the limited amount of information is available. Furthermore, current weather prediction models are not sufficient to predict more localized events (e.g. thunderstorms). Therefore, it is necessary to minimize the impacts of uncertain events and utilize powerful computing techniques or machine to predict even a simple event so that it would be possible to prevent heavy damages and loss of property and life. For example, analyzing huge amounts of weather data will be quite useful for sending necessary warnings regarding power cut, water logs, wind effects, and required preparedness.

TABLE III. QUANTUM MACHINE LEARNING APPROACHES FOR WEATHER PREDICTION

Authors & Citation	Year	Quantum Machine Learning approaches/methods	Advantages/Limitations
Bobier J.F., et al [11]	2020	Quantum computing for addressing major emissions. Climate change related-Quantum simulations: BASF, HQS	Advances in hardware and software are required to create breakthrough in the carbon-intensive processes by developing more efficient chemical catalysts. -low-carbon technologies are needed to deal with climate change problems
Scanlan K et al [12]	2022	Forecasting the weather using Quantum Computers	Weather analysis on huge amounts of data by using classical computers may not be fast enough as it involves several dynamic variables (e.g., temperature, humidity, atmospheric air pressure, etc), for dealing with unexpected weather conditions.
Ho A et al [13]	2020	Tensorflow Quantum (TFQ)-An open source library for Quantum Machine Learning	An open source library announced for the rapid prototyping of Quantum –based Machine learning models. -TFQ integrated Cirq –It provides high performance simulation - It supports implementation of both discriminative and generative models -It is compatible with existing TensorFlow APIs
Alamitos L et al [14]	2022	Quantum computing in climate change analysis	Quantum machine learning will greatly reduce the impacts of weather on renewable energy in energy sectors. -Fuel cells have the potential to achieve zero carbon emissions, and to efficiently store huge amounts of energy. -Example: Quantum computing has the potential to identify chemical catalysts and hydrogen chemical reaction with oxygen for generating clean energy.
O'Brien J et al [15]	2022	Quantum computing as an innovative climate change solutions	Quantum computing can help scientists in simulating large number of complex molecules. -Example: it can help them to identify new catalysts for sucking carbon in the atmosphere. -it requires large-scale qubits, efficient error-correction
Leprince-Ringuet D et al [16]	2021	Quantum computing as a tool to deal with climate change	Quantum computers have exponential computing power and will help researchers to solve complex problems more efficiently. -Example: In agriculture, quantum computing will be able to reduce the power needed to manufacture fertilizers -it can help us to create more efficient batteries and better materials for solar cells or carbon sucking.

Although supercomputers are designed to handle complex tasks and to provide accurate results, they require more computation in terms of brute force. Hence, the need for harnessing the power of qubits by using quantum machine learning becomes increasingly important in finding solutions to the computationally complex problems. An overview of quantum machine learning studied from an article on quantum machine learning [17]. Table III presents some examples and methods of quantum machine learning in weather prediction problems. Reference [18] proposed a method for weather forecasting, tried to develop an automatic device using microcontroller. For microclimatic parameter estimation for productive Agronomics, supervised learning applied in [19].

III. Future Direction and conclusion

Future directions: In future, the main focus in this research field will be on the development of quantum machine learning solutions that will involve a combination of techniques from quantum mechanics, machine learning, deep learning, data science, natural language processing, and others towards building more accurate and efficient weather prediction models. Furthermore, new algorithms will be developed to analyze the data more efficiently by using quantum computing techniques and quantum machine learning. The results of new simulation models can be utilized to formulate climate-risk mitigation strategies and best practices that will be very helpful to satisfy sustainable development goals and to tackle challenges the global society is facing.

Conclusion: This paper presented a study on the latest developments and trends of quantum machine learning along with various challenges, applications, and examples. In addition, the methods for combining quantum computing and machine learning to create more accurate and more efficient quantum weather prediction models have been studied with suitable examples.

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