Quantum-Enhanced Parameter Efficient Learning for Typhoon Trajectory Forecasting Using Neutral Atom Quantum Computing

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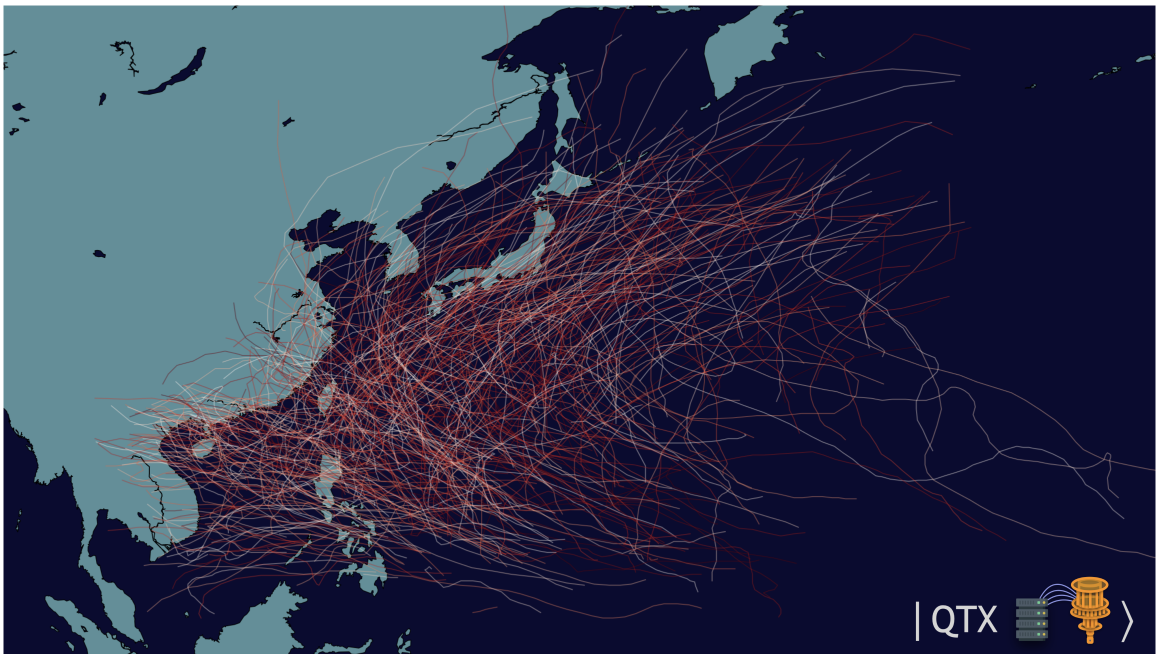

Sustainability Impact Study

"Sustaining the Future with Quantum-Enhanced Intelligence."

— Team QTX

ABSTRACT

This sustainability impact study report explores the integration of quantum computing into typhoon trajectory forecasting to enhance predictive accuracy, computational efficiency, and environmental sustainability. Traditional forecasting models face significant computational limitations, requiring extensive resources while struggling with the inherent complexity of atmospheric dynamics. In response, we investigate the application of Quantum-Train (QT) and Quantum Parameter Adaptation (QPA)—quantum-enhanced learning methodologies—that generate parameters using quantum neural networks solely during training, eliminating the need for quantum hardware in inference. This novel approach significantly reduces computational overhead while maintaining high forecasting accuracy. By leveraging hybrid quantum-classical techniques, this study demonstrates the potential for quantum computing to optimize energy consumption, minimize CO_2 emissions, and improve climate resilience through more efficient and scalable weather prediction models. The findings of this report highlight how quantum-enhanced forecasting can contribute to global sustainability efforts, aligning with United Nations Sustainable Development Goals (SDGs) 13, 14, and 15 by enabling proactive disaster response and ecosystem protection.

Contents

1 Introduction

1.1 Context and Significance

Typhoons, also known as tropical cyclones or hurricanes, are among the most devastating natural disasters, causing significant loss of life, property damage, and economic disruption. Accurately forecasting their trajectories is crucial for effective disaster preparedness and mitigation. However, traditional forecasting methods face challenges due to the complex and dynamic nature of these weather systems. Integrating advanced technologies, such as quantum computing, into forecasting models presents a promising avenue to enhance prediction accuracy and contribute to global sustainability efforts.

Satellite image of typhoon.

2009 Morakot typhoon in Taiwan.

2001 Nari typhoon in Taiwan.

Figure 1: Typhoons. (Central Weather Administration, 2025; CTWant, 2025)

1.2 Challenges in Typhoon Trajectory Forecasting

Forecasting typhoon trajectories involves predicting the path that these powerful storms will follow. Accurate predictions are vital for issuing timely warnings, orchestrating evacuations, and implementing other disaster response measures. However, several challenges impede precise forecasting:

1. **Complex Atmospheric Dynamics**: Typhoons are influenced by a multitude of atmospheric variables, including wind patterns, humidity levels, sea surface temperatures, and atmospheric pressure systems. The intricate interactions among these factors make modeling their behavior exceedingly complex.
2. **Data Limitations**: Despite advancements in satellite technology and meteorological observations, there remain gaps in data coverage, particularly over vast oceanic regions where typhoons typically develop and travel. These data deficiencies can lead to inaccuracies in initial conditions for forecasting models.
3. **Computational Constraints**: High-resolution models that can capture the fine-scale processes of typhoons require substantial computational resources. Traditional supercomputers, while powerful, may still struggle to process these complex models in a timely manner, limiting the ability to provide real-time forecasts.
4. **Rapid Intensity Changes**: Typhoons can undergo sudden changes in intensity, which are challenging to predict. These rapid intensification or weakening events significantly impact the accuracy of trajectory forecasts and pose additional challenges for disaster preparedness.

1.3 Quantum Computing: A Paradigm Shift in Forecasting

Quantum computing represents a transformative approach to addressing the computational challenges inherent in typhoon forecasting. Unlike classical computers, which process information in binary bits (0s and 1s), quantum computers utilize quantum bits or qubits. Qubits can exist in multiple states simultaneously—a property known as superposition—enabling quantum computers to perform many calculations at once. This capability allows for the processing of vast amounts of data and the simulation of complex systems more efficiently than classical computers.

1.4 Potential Benefits of Quantum-Enhanced Forecasting

1. **Improved Accuracy**: Quantum computing can handle the vast datasets and complex models required for accurate typhoon trajectory forecasting, potentially leading to more precise predictions.
2. **Faster Processing**: The ability of quantum computers to perform parallel computations can significantly reduce the time required to run forecasting models, facilitating real-time or near-real-time predictions.
3. **Enhanced Modeling Capabilities**: Quantum computing can simulate complex atmospheric interactions at a granular level, improving the representation of physical processes in forecasting models.

2 Challenge Alignment & Problem Context

2.1 Alignment with Sustainable Development Goals (SDGs)

Harnessing quantum computing for enhanced typhoon trajectory forecasting model training directly supports global efforts in climate resilience, ecosystem protection, and biodiversity conservation. By leveraging advanced computational capabilities, quantum computing enhances model compression, enabling proactive measures to safeguard both human communities and natural ecosystems.

- **SDG 13: Climate Action** – The increasing frequency and intensity of extreme weather events due to climate change necessitate more accurate and timely forecasting. Quantum-enhanced climate models allow for superior typhoon trajectory prediction, enabling governments and disaster response teams to implement early warning systems. This reduces the adverse impacts of climate-related disasters, enhances preparedness, and supports adaptation strategies for vulnerable regions.
- **SDG 14: Life Below Water** – Coastal and marine ecosystems, including coral reefs, mangroves, and fisheries, are highly vulnerable to typhoons. Enhanced forecasting enables better planning to minimize ecological damage, prevent habitat destruction, and reduce the risk of large-scale marine biodiversity loss. By improving resilience against climate-driven disruptions, quantum computing supports sustainable ocean conservation and the protection of marine life.
- **SDG 15: Life on Land** – Severe storms and typhoons cause deforestation, soil erosion, and habitat destruction, threatening terrestrial biodiversity. More precise forecasting allows for the strategic relocation of vulnerable species, improved land-use planning, and better conservation efforts. Additionally, early warning systems help mitigate agricultural losses, ensuring food security and maintaining ecological balance.

Quantum computing-driven improvements in climate modeling facilitate impactful conservation and adaptation strategies, reinforcing the global commitment to sustainability and resilience.

Figure 2: Overview of the United Nations Sustainable Development Goals. (United Nations General Assembly, 2015; Colglazier, 2015)

2.2 Significance of Typhoon Trajectory Forecasting

Typhoons represent one of the most devastating categories of natural disasters globally, significantly contributing to economic disruption, loss of human life, and extensive environmental damage. Accurate forecasting of typhoon trajectories is essential, enabling effective disaster preparedness, resource mobilization, and proactive risk mitigation. Improved accuracy in forecasting not only helps reduce immediate damages but also contributes to sustained economic stability, human security, and environmental sustainability.

Moreover, reliable predictive systems allow governments, private sector entities, and local communities to implement preemptive measures, substantially reducing vulnerability and enhancing resilience in affected regions. Better forecasting facilitates informed decision-making, which is critical for coordinating evacuation plans, deploying resources efficiently, and reducing overall disaster response costs. Therefore, advancements in typhoon forecasting technology hold substantial significance in enhancing global disaster preparedness and response.

2.2.1 Economic Impact

Typhoons have substantial economic repercussions, affecting both immediate and long-term financial stability. Recent data highlights the severity of the economic implications, with natural disasters causing an estimated $320 billion in global losses in 2024 alone. Typhoons constitute a considerable portion of these losses, especially impacting developing and densely populated regions (Financial Times, 2024). For instance, Typhoon Yagi (Wikipedia Contributors, 2024a;b) alone accounted for around $14 billion in damages within Southeast Asia, demonstrating how severely these weather events can disrupt regional economies.

The economic impacts include destruction of infrastructure, disruption of trade and supply chains, agricultural devastation, and increased fiscal pressures on government budgets for reconstruction and rehabilitation. These disruptions ripple across local economies, affecting businesses, employment, and economic growth for extended periods following the event. Accurate forecasts can significantly mitigate these economic impacts by facilitating timely evacuations, safeguarding critical infrastructure, minimizing operational downtimes, and optimizing disaster response expenditure.

2.2.2 Human Cost

The human toll of typhoons is profound and multi-dimensional, encompassing fatalities, physical injuries, psychological distress, and massive displacement of populations. Globally, in 2024, approximately 11,000 lives were lost due to natural disasters, with typhoons representing a significant proportion of these fatalities (Financial Times, 2024). In Southeast Asia, Typhoon Yagi alone was responsible for around 850 fatalities, highlighting the immense risk these events pose to human life.

Additionally, millions of individuals are displaced annually by typhoons, creating prolonged humanitarian crises characterized by overcrowding in evacuation centers, limited access to essential services such as healthcare, sanitation, and education, and heightened vulnerabilities to secondary health emergencies. Long-term psychological impacts, including post-traumatic stress disorder and anxiety, further exacerbate the human toll. Accurate and timely typhoon forecasting enhances the capacity for effective evacuation, targeted humanitarian aid, and sustained long-term recovery planning, thereby substantially reducing the human cost associated with these events.

2.2.3 Environmental Consequences

Typhoons inflict significant environmental damage, often resulting in long-lasting ecological disruptions. Primary environmental impacts include severe deforestation, loss of biodiversity, extensive soil erosion, and widespread contamination of water resources. These consequences disrupt local ecosystems and diminish their resilience against future climatic events, compounding vulnerability and exacerbating environmental degradation over time.

Typhoons frequently devastate critical habitats such as mangroves, coral reefs, and coastal wetlands, which perform essential ecological functions including carbon sequestration, biodiversity conservation, and natural coastal defenses against erosion and flooding. Restoration of these damaged environments is often costly and complex, necessitating prolonged recovery periods. Thus, enhanced forecasting is vital for implementing effective ecological protection measures and minimizing long-term environmental degradation.

2.3 Case Study: The Philippines

The Philippines exemplifies a region of acute vulnerability to typhoons, routinely experiencing around 20 major storms each year (Contributors, 2025). This high frequency is largely attributed to the country's geographic location in the Pacific Typhoon Belt, where warm ocean waters and prevailing wind patterns converge to intensify storm activity. Compounding the risk is the archipelagic nature of the Philippines, which disperses populations across thousands of islands, making evacuation and resource distribution particularly complex.

A salient illustration of this vulnerability is Typhoon Toraji, which devastated the northern Philippines, resulting in widespread structural damage, the displacement of thousands of residents, and significant disruptions to local economies and daily life (Gomez, 2024). Aside from immediate destruction, these powerful storms often trigger secondary hazards such as flooding, landslides, and waterborne disease outbreaks, further straining local healthcare systems and social services. The ensuing economic setbacks reverberate across multiple sectors, from agriculture and fisheries to tourism, prolonging the path to recovery for affected communities.

Such events underscore the urgent need for more accurate forecasting mechanisms, stronger disaster preparedness frameworks, and more resilient community-level strategies. Enhanced early warning systems, bolstered by real-time data analytics and state-of-the-art computational modeling, can give government agencies, first responders, and local stakeholders a critical window of time to mobilize resources, plan evacuations, and safeguard infrastructure. Strengthening these capacities is essential for mitigating the human, social, and economic toll of typhoons, not only in the Philippines but also in similarly exposed regions worldwide.

2.4 Limitations of Classical Forecasting Methods

Traditional typhoon forecasting methods face several inherent limitations, significantly affecting their predictive accuracy and effectiveness. One major constraint is data scarcity, especially in remote oceanic regions where typhoons originate and intensify. Limited observational data availability hinders accurate initial condition modeling, thereby reducing the reliability and precision of forecasts and leading to uncertainties in emergency planning and preparedness efforts.

Furthermore, classical forecasting methods require considerable computational power to deliver high-resolution forecasts in a timely manner, often exceeding the resources available for real-time applications. In practice, such methods rely on a small number of global HPC centers operating in isolation from each other. Because each predictive model is extremely large, it is impractical for these HPC facilities to co-develop or share inferences, resulting in a fragmented "competitive" model environment rather than a cooperative one. Additionally, the massive computational load of these large-parameter models consumes vast amounts of energy and remains relatively inefficient. Addressing these limitations through advanced technological developments—ranging from enhanced remote sensing technologies to more efficient HPC and machine learning algorithms—is critical to improving the reliability and efficacy of typhoon trajectory forecasting.

2.5 Advancements in Forecasting: Quantum Computing

Integrating quantum computing into typhoon trajectory forecasting offers a transformative pathway to overcoming these long-standing challenges. Quantum hardware and algorithms can process vast amounts of data and simulate complex physical systems more efficiently than their classical counterparts, promising notable improvements in both speed and accuracy. In response to the limitations highlighted above, this research proposes a Quantum-HPC co-design framework that significantly reduces the number of parameters in typhoon trajectory prediction models.

By leveraging privacy-preserving quantum-training techniques, multiple HPC centers can collaboratively train and refine models without exposing sensitive regional data, thereby fostering global cooperation rather than isolated competition. This synergy between HPC and quantum computing not only streamlines the computational pipeline but also enhances energy efficiency. Methods like Quantum-Train (QT) and Quantum Parameter Adaptation (QPA) further reduce the number of trainable parameters, enabling faster model convergence while maintaining accuracy. The result is a more sustainable and accessible forecasting solution that can be deployed on existing classical infrastructure, democratizing access to high-performance tools even for regions with limited computational resources.

Collectively, these advancements equip governments, communities, and individuals with more accurate and timely typhoon trajectory forecasts. The lead time gained through improved modeling allows for more effective disaster preparedness, risk mitigation, and resource allocation—ultimately reducing the devastating socioeconomic impacts of incoming typhoons.

3 Expected Sustainability Benefits

The integration of quantum-enhanced forecasting methods in meteorology presents significant environmental, social, and economic benefits. This section explores these advantages in detail, aligning them with the Sustainable Development Goals.

3.1 Environmental Benefits

3.1.1 Reduction in Energy Consumption

Traditional high-performance computing systems used for weather forecasting are energy-intensive, contributing to substantial carbon emissions. In the hardware perspective, quantum computing could offers a more energy-efficient alternative. For instance, photonic quantum chips, which utilize light for information transfer, operate at room temperature and consume less energy compared to traditional silicon-based systems. This advancement not only enhances computational efficiency but also aligns with environmental sustainability goals (Ephos, 2023).

From the perspective of QPA applied to this typhoon trajectory forecasting project, as discussed in Sec. 4.3 of the technical report, we analyze the significant computational and energy efficiency advantages of QPA over traditional classical training methods. In classical ML, the computational cost of training is directly proportional to the number of parameters being optimized. Large neural networks—often containing millions to billions of parameters—require high-performance GPU clusters, resulting in substantial energy consumption. The training cost for a classical deep learning model can be expressed as:

$$C_{\text{classical}} = O(P \cdot D), \tag{1}$$

where P denotes the number of trainable parameters, and D represents the number of training iterations. Large-scale models, such as transformers and deep neural networks, can reach hundreds of billions of parameters, raising concerns over the growing energy demands of AI research and deployment. However, QT dramatically reduces the number of trainable parameters by scaling it to a polylogarithmic order, as described in Sec. 2 of the technical report. The trainable parameter count under QT follows:

$$P_{\text{quantum}} = O(polylog(P)). \tag{2}$$

Since training complexity in classical deep learning typically scales at least linearly with the number of parameters, this exponential reduction in parameter count translates into a significantly lower computational workload for QPA-based training. The overall cost function for quantum-enhanced training is then:

$$C_{\text{quantum}} = O(polylog(P) \cdot D_{\text{quantum}}), \tag{3}$$

where D_{quantum} denotes the number of quantum-enhanced training iterations. This optimization leads to a substantial reduction in floating-point operations (FLOPs) required for training, directly resulting in lower energy consumption and making large-scale climate forecasting models more sustainable and computationally feasible.

3.1.2 Decrease in CO_2 Emissions

The significant reduction in computational workload achieved through QPA not only lowers energy consumption but also has a direct impact on reducing CO_2 emissions. The training of large-scale deep learning models is known to be energy-intensive, often requiring high-performance GPU clusters operating for extended periods. Studies have shown that training a single large deep learning model can emit as much CO_2 as five cars over their entire lifetime (Strubell et al., 2020).

Given that the energy demand of classical deep learning models is proportional to their parameter count, the exponential reduction in trainable parameters enabled by QPA significantly mitigates the environmental impact. The decrease in computational cost leads to:

$$E_{\text{quantum}} = O(polylog(P) \cdot E_{\text{classical}}), \tag{4}$$

where E_{quantum} and $E_{\text{classical}}$ represent the respective energy consumption for QPA-based and traditional training methods. Since power consumption in GPU clusters translates directly to carbon emissions, reducing training complexity leads to lower electricity usage, particularly in regions where power grids rely on fossil fuels.

Moreover, many climate forecasting models require continuous retraining to adapt to new meteorological patterns. By leveraging QPA, we make it feasible to train these models more frequently without incurring excessive carbon footprints. This makes large-scale typhoon forecasting not only computationally efficient but also environmentally sustainable, aligning with global efforts to combat climate change (**SDG 13: Climate Action**).

Broader Sustainability Impact

- **Lower AI Carbon Footprint** $\rightarrow$ Reduces energy demand for large-scale forecasting models.
- **Greener AI Infrastructure** $\rightarrow$ Enables sustainable AI deployments in climate science.
- **Scalable Quantum Integration** $\rightarrow$ Prepares for future quantum-powered AI with minimal environmental impact.

The adoption of Quantum-Enhanced AI for typhoon forecasting serves as a pioneering step toward a more sustainable future, showcasing how quantum computing can contribute to both climate resilience and green technology development.

3.1.3 Resource Optimization

Quantum computing enables more accurate and efficient data processing, leading to optimized resource utilization. In meteorology, this means better prediction models that can inform agricultural practices, water resource management, and disaster preparedness, thereby minimizing environmental degradation and promoting sustainable use of natural resources.

3.2 Social Impact

Improved forecasting accuracy or reduce the training cost through quantum computing allows for more reliable early warning systems. This enhancement leads to timely evacuations and disaster response strategies, thereby reducing casualties and injuries during natural disasters. For example, accurate predictions of typhoon trajectories can provide communities with sufficient time to implement safety measures, thereby saving lives and reducing harm. With precise weather forecasts, communities can better prepare for adverse weather conditions, strengthening their resilience. This preparedness includes infrastructure reinforcement, efficient resource allocation, and informed urban planning, all of which contribute to the community's ability to withstand and recover from disasters. Accurate weather forecasting directly impacts public safety by informing citizens about potential hazards. This information allows individuals to make informed decisions regarding travel, outdoor activities, and other daily routines, thereby enhancing overall quality of life.

3.3 Economic Benefits

Quantum computing's efficiency leads to lower energy consumption and operational costs. This reduction translates to significant savings for meteorological departments and research institutions, allowing for the reallocation of funds to other critical areas. Accurate forecasts enable proactive measures to protect infrastructure, such as reinforcing buildings and bridges before a predicted natural disaster. These precautions result in reduced repair and replacement costs post-disaster, leading to substantial economic savings. Improved predictive capabilities allow businesses to prepare for and mitigate the impacts of adverse weather conditions. For instance, supply chains can be adjusted in anticipation of a storm, reducing economic losses and maintaining business continuity.

3.4 Examples

3.4.1 Reducing Transportation Emissions during Evacuations

Consider a coastal city facing an approaching typhoon. Traditional forecasting methods may provide a broad prediction window, leading to large-scale, inefficient evacuations. Quantum-enhanced forecasting can offer more precise trajectory predictions, allowing for targeted evacuations. This precision reduces the number of vehicles on the road, leading to lower fuel consumption and decreased transportation-related CO_2 emissions. Additionally, efficient evacuation plans minimize traffic congestion, further reducing environmental impact and enhancing public safety.

3.4.2 Reduction During Retraining

As mentioned above, many climate forecasting models require continuous retraining to adapt to evolving meteorological patterns. By leveraging QPA, we enable more frequent model updates while significantly reducing carbon emissions, making large-scale climate forecasting both computationally and environmentally sustainable.

4 Scalability & Deployment Roadmap

The integration of quantum-enhanced forecasting methodologies, such as Quantum-Train (QT) and Quantum Parameter Adaptation (QPA), offers transformative potential in meteorological predictions. This section outlines a strategic roadmap for deploying these technologies, emphasizing immediate actions and long-term objectives aligned with Sustainable Development Goals (SDGs).

4.1 Short-Term Goals

- **Exploring Hybrid Analog-Digital Quantum Computing with Pasqal's Platform**: Investigate the potential of Pasqal's neutral atom quantum processors for hybrid analog-digital computing. This exploration will focus on leveraging continuous quantum evolution and digital gate-based optimizations to improve the efficiency and scalability of typhoon trajectory forecasting models. By integrating hybrid computing paradigms, this approach aims to minimize resource overhead while maximizing predictive performance in extreme weather modeling.
- **Collaboration with Meteorological Agencies**: Initiate partnerships with national weather services to implement QT and QPA methodologies in existing forecasting models. This collaboration aims to validate the efficacy of quantum-enhanced predictions in real-world scenarios. Integrate quantum-enhanced models with current data assimilation systems to assess improvements in forecast accuracy and computational efficiency. Conduct rigorous testing to benchmark performance against traditional models.

4.2 Long-Term Vision

Quantum-enhanced typhoon forecasting represents a forward-looking initiative that addresses current computational and collaborative bottlenecks while laying the groundwork for a globally scalable, energy-efficient system. In pursuit of lasting impact—both scientifically and operationally—this vision aims to integrate quantum computing advancements with existing meteorological infrastructures, thereby enabling broad adoption and continuous technological evolution.

4.2.1 Global Scalability

Standardization and Scalable Infrastructure A critical component of realizing global scalability involves establishing standardized quantum-enhanced forecasting methodologies through collaboration with international meteorological organizations. Such partnerships can foster unified protocols for data formats, model architectures, and validation criteria, ensuring consistency and interoperability across various national weather services. Concurrently, close collaboration with quantum computing companies is essential to develop hardware and software architectures that can meet large-scale forecasting demands. By co-designing scalable quantum infrastructure with weather agencies and HPC centers, researchers can optimize computation pipelines, reduce energy consumption, and facilitate cost-effective upgrades as quantum hardware matures. This dual strategy—standardizing frameworks and scaling infrastructures—bolsters inclusive adoption, especially for regions with limited computational resources, thus expanding the global reach of quantum-enhanced forecasting.

4.2.2 Market Adoption and Industrial Integration

Industry and Energy Sector Integration Beyond governmental applications, quantum-enhanced forecasting has the potential to deliver transformative benefits to multiple industrial sectors. Private weather service providers can adopt these refined forecasting models to deliver highly accurate predictions to agriculture, aviation, logistics, and tourism industries. Enhanced reliability in weather forecasts will enable precision agriculture (e.g., optimal planting times, irrigation management), safer flight routing, more efficient shipping schedules, and improved event planning, thereby reducing operational costs and improving overall service quality.

Moreover, the enhanced forecasts can directly support **SDG 7: Affordable and Clean Energy** by helping to optimize renewable energy production. For instance, accurate wind speed and solar irradiance forecasts allow for improved planning and distribution of resources in power grids, leading to more stable and efficient energy systems. This, in turn, reduces the reliance on fossil fuels and mitigates carbon emissions—key objectives in the global transition toward clean and sustainable energy.

4.3 Example Roadmap: Integration within National Weather Services

The integration of Quantum-Train (QT) and Quantum Parameter Adaptation (QPA) methodologies into national weather services requires meticulous planning and multi-phase execution. Below is a structured roadmap outlining the key phases, objectives, and metrics for evaluating both technical feasibility and operational readiness.

4.3.1 Implementation Roadmap

- **Phase 1: Feasibility Study (Year 1)**
  - *Assessment of Compatibility*: Conduct an in-depth analysis to ensure that QT and QPA models align with existing weather forecasting infrastructures, including data assimilation pipelines, HPC architectures, and operational workflows.
  - *Pilot Projects*: Initiate collaborative pilots with select national weather services to gather empirical data on computational requirements and forecast improvements under controlled testing conditions.
  - *Key Deliverable*: A feasibility report outlining potential performance gains, approximate energy savings, and an initial risk analysis to guide further development.
- **Phase 2: Pilot Deployment (Years 2-3)** Implement quantum-enhanced models in operational settings.
  - *Parallel Implementation*: Integrate quantum-enhanced models in tandem with traditional forecasting systems, allowing side-by-side performance evaluation without disrupting routine operations.
  - *Stakeholder Feedback*: Collect insights from meteorologists, governmental agencies, and local communities on forecast reliability, accuracy, and user-friendliness to refine the quantum-enhanced approach iteratively.
  - *Key Deliverable*: Comprehensive performance metrics—such as lead time accuracy, reduction in false alarms, and energy consumption—plus a stakeholder report on adoption challenges and recommended improvements.

- **Phase 3: Full Integration and Expansion (Years 4-5)** Achieve full integration of quantum-enhanced forecasting across national weather services.
  - *Operational Roll-Out*: Transition national weather services from traditional models to fully quantum-enhanced systems, incorporating best practices derived from the pilot phase.
  - *Regional Outreach*: Extend the deployment to regional and local forecasting agencies, ensuring that smaller stations and communities can leverage high-precision models.
  - *Key Deliverable*: Institutionalized quantum-enhanced forecasting operations with standardized protocols for continual model updates, HPC-quantum hardware synchronization, and energy efficiency assessments.

4.4 Scalability & Deployment Considerations

Short-Term Considerations: Ensuring the seamless integration of quantum-enhanced models requires assessing their compatibility with existing computational infrastructure and developing middleware solutions. Additionally, resource allocation is critical—identifying necessary quantum computing resources and addressing initial scalability challenges will facilitate smoother adoption.

Long-Term Considerations: A sustainable deployment strategy requires investment in advanced quantum infrastructure and collaboration with technology providers to meet forecasting demands. Policy and regulatory engagement are essential for guiding quantum technology adoption, addressing data privacy and security concerns. Furthermore, continuous improvement through research and feedback mechanisms will drive advancements in quantum-enhanced forecasting methodologies.

4.5 Platform Comparison: Why Neutral Atoms?

Neutral-atom quantum devices hold particular promise in large-scale and reconfigurable quantum computing, primarily due to their use of hyperfine or electronic states in atoms such as rubidium or cesium. Entangling interactions, often implemented via the Rydberg blockade mechanism, enable both digital and analog computational paradigms across hundreds to thousands of atoms arranged in optical-tweezer arrays. These attributes are especially advantageous for the Quantum-Train framework, where quantum circuits generate compact parameter representations for large-scale classical models. Unlike superconducting circuits, neutral-atom platforms do not require dilution refrigerators, lowering both hardware overhead and operating complexity. Moreover, the reconfigurable geometry of neutral-atom arrays offers flexible connectivity that greatly benefits data-intensive hybrid algorithms, where qubit coupling patterns can be tailored to specific computational tasks.

As part of the emerging quantum-HPC ecosystem, the integration of neutral-atom platforms with classical supercomputers paves a clear path to resource-efficient quantum-enhanced learning. By leveraging QT and Quantum Parameter Adaptation, one can substantially compress classical model parameters, thereby reducing both training costs and energy consumption. Under these methods, a quantum processor computes parameter subsets and transfers them seamlessly to classical neural network architectures, obviating the need for quantum hardware at inference. Additionally, operation at near-ambient temperatures and the ability to mix digital and analog modes further underscore the potential for scaling neutral-atom devices in distributed or cloud-based quantum systems. Taken together, these features position neutral atoms as an especially compelling platform for the next generation of large-scale, hybrid quantum-classical machine learning applications.

Table 1: Comparison of prominent quantum computing platforms (bold text indicates relative advantages).

Platform	Neutral Atoms	Superconducting Circuits	Ion Traps	Spin Defects
Qubit Encoding	Hyperfine or electronic states (Rb, Cs), often excited to Rydberg levels	Josephson junctions (e.g., transmon qubits)	Hyperfine or Zeeman sublevels in trapped ions (e.g., Ca^+, Yb^+)	Color centers in solids (e.g., NV centers in diamond)
Coherence and Error Rates	**Single-qubit gates with high fidelity**, two-qubit fidelities still improving; coherence limited by atom loss and laser stability	Single-qubit fidelity often exceeds 99.9%, two-qubit above 99%; sensitive to fabrication variations and crosstalk	Very long coherence times, two-qubit gates reaching 98–99.9% fidelity; trade-off with gate speed	Potentially long coherence (seconds), but error rates depend strongly on defect quality and local environment
Scalability and Qubit Count	**Intrinsically scalable to hundreds or thousands of atoms in reconfigurable arrays**	Commercial systems reach over 100 qubits, but wiring and cryogenic overhead complicate scaling beyond this range	Systems in the tens to hundreds of ions, with engineering challenges for thousands	Typically demonstrated in small ensembles; scaling to larger registers remains in early research
Connectivity	**Reconfigurable 2D or 3D layouts enable flexible entangling gates through Rydberg interactions**	Generally restricted to fixed couplers; SWAP operations often needed for distant qubits	All-to-all coupling in principle via collective ion motion, but parallel operations can be challenging	Often requires photon-mediated entanglement or short-range interactions; architectures are less mature
Gate Speed / Fidelity	Gate times in microseconds, **single-qubit fidelity** $> 99.5\%$, two-qubit often above 94–99% in prototypes	Typical gate times in tens of nanoseconds, with high fidelities near 99%	Gate durations from microseconds to milliseconds, with high fidelity but slower speeds	Gate speeds vary; fidelity limited by local disorder, inhomogeneities, and control precision
Operating Temperature	**Room temperature or near-ambient**	Requires dilution refrigerator at millikelvin temperatures	Operates in ultra-high vacuum at room temperature	Often room temperature in solid-state environments
Maturity and Challenges	**Allows digital-analog hybrid computation**; two-qubit gate improvements and laser control remain active research	Most mature industrial ecosystem; overhead from cryogenics and wiring as scale grows	Excellent coherence but scalable multi-qubit gating and parallelism can be complicated	Ideal for sensing but implementing multi-qubit networks is still in developmental stages
Quantum-Train Deployment	**Large, reconfigurable arrays and no cryogenics make neutral atoms highly promising for multi-node or distributed QT frameworks**	Mature gates and readout but cryogenics complicate scaling; mid-scale QT is still feasible but energy-intensive	All-to-all coupling helps parameter generation; slower gates and parallelization challenges limit large-scale QT	Excellent single-qubit coherence but limited multi-qubit gating; less suitable for extensive QT-based training

5 Key Performance Indicators & Quantum Energy Efficiency

5.1 Reduction in CO_2 Emissions Compared to Classical Methods

The transition from classical to quantum computing in forecasting models has the potential to significantly reduce CO_2 emissions. Traditional supercomputers are highly energy-intensive, contributing to large carbon footprints. For instance, the **Frontier supercomputer** operates at approximately **21 megawatts (MW)**, consuming around **504 megawatt-hours (MWh) per day**. In contrast, **superconducting qubit-based quantum computers** require only about **25 kilowatts (kW), or 0.6 MWh daily**, making them approximately **1,000 times more energy-efficient** than classical supercomputers. **Neutral atom quantum devices**, such as those developed by **Pasqal**, are even more energy-efficient, consuming only **7 kW** (**?**).

To estimate the potential **CO_2 emissions savings** in an **idealized near-future scenario**, we leverage **Pasqal's sustainability benchmark** along with the previously derived runtime assumptions. The following considerations are taken into account:

1. **QPA Execution on the Orion Series:** The expected qubit requirement for QPA is only in the range of **dozens of qubits** on a **100–200 qubit** device. The remaining qubits are assumed to be allocated for **quantum error correction**, ensuring higher reliability during execution.
2. **Post-Orion Series with Enhanced Parallelization:** The **Post-Orion series** (400–1000 qubits) offers a **10× parallelization advantage** over the Orion series, enabling **10× more circuits** to be executed simultaneously. This effectively reduces the runtime to **10%** of that required on Orion.
3. **Classical GPU Comparison:** The **Joliot-Curie Rome supercomputer** features over **42× more GPUs** than a standard GPU server. Taking into account both **parallelization and superior GPU architecture**, we estimate an overall **100× speedup** relative to a basic GPU server.

By applying these assumptions and using **Pasqal's sustainability benchmark**, we compute the resulting **CO_2 emissions**, as illustrated in Fig. 3.

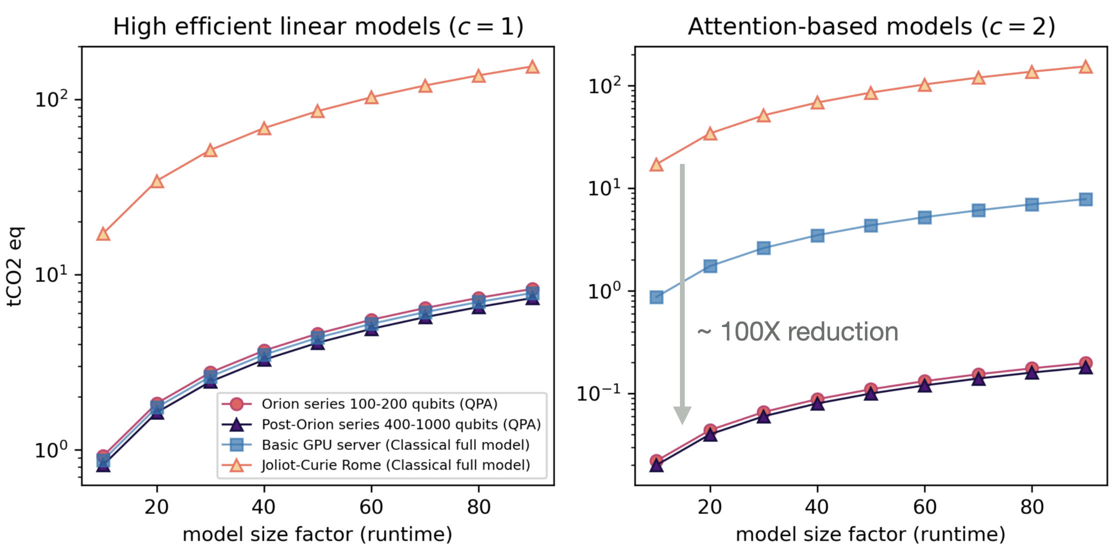

Figure 3: Estimated tCO_2 emissions for QPA on Pasqal's Orion and Post-Orion series compared to classical full-model training on a basic GPU server and the Joliot-Curie Rome supercomputer, demonstrating the sustainability advantage of quantum-enhanced parameter-efficient learning across both linear ($c = 1$) and attention-based ($c = 2$) models.

Fig. 3 presents a comparative analysis of tCO_2 equivalent emissions across different computational platforms for machine learning (ML) model training. The analysis considers both highly efficient **linear models** ($c = 1$) and more **computationally demanding attention-based models** ($c = 2$), as described in the previous section. The x-axis represents the model size factor (runtime), while the y-axis quantifies the estimated emissions. The comparison includes QPA implementations on Pasqal's Orion and Post-Orion series, alongside classical full-model training on both a basic GPU server and the Joliot-Curie Rome supercomputer.

In the **left panel** (linear models, $c = 1$), the results indicate that QPA implementations on the Orion (100–200 qubits) and Post-Orion (400–1000 qubits) series exhibit significantly lower emissions compared to classical training on the Joliot-Curie Rome supercomputer. The emissions from QPA remain relatively stable across different model sizes, demonstrating the efficiency of quantum computing in reducing the carbon footprint of parameter-efficient models. Interestingly, classical full-model training on a basic GPU server shows emissions comparable to those of QPA, suggesting that for sufficiently simple models, traditional GPU-based training may still be a viable and energy-efficient option.

In the **right panel** (attention-based models, $c = 2$), where computational demands increase quadratically with model size, the advantages of QPA become even more pronounced. While QPA on Orion and Post-Orion maintains consistently low emissions, classical full-model training on a basic GPU server experiences a significantly steeper increase in emissions. The Joliot-Curie Rome supercomputer, despite its computational power, exhibits the highest emissions, reinforcing the substantial environmental cost of large-scale deep learning models trained on traditional high-performance computing (HPC) infrastructures.

These results underscore the significant **sustainability benefits** of QPA-based quantum computing. By leveraging quantum-enhanced parameter-efficient learning, QPA not only reduces computational overhead but also drastically lowers carbon emissions compared to classical full-model training. As quantum hardware continues to advance, integrating QPA into large-scale ML workflows holds the potential to revolutionize AI sustainability—making high-performance training both computationally and environmentally efficient.

5.2 Improved Energy Efficiency of Quantum vs. Classical Computing Approaches

Quantum computing's operational principles contribute to its enhanced energy efficiency. Unlike classical computers that rely on irreversible logic gates leading to energy dissipation, quantum computers utilize unitary operations, which are inherently reversible and do not dissipate energy through information loss. This characteristic aligns with Landauer's principle, which states that irreversible computation results in energy dissipation (Landauer, 1961). Consequently, quantum computing can perform certain computations with significantly reduced energy consumption compared to classical methods.

5.3 Broader Socio-Economic Impacts

5.3.1 Increased Accessibility of High-Performance Forecasting Models

The enhanced energy efficiency and computational capabilities of quantum computing can democratize access to high-performance forecasting models. Organizations previously constrained by the high operational costs of classical supercomputers can leverage quantum computing to implement sophisticated models without incurring prohibitive energy expenses. This accessibility can lead to more widespread adoption of advanced forecasting tools across various sectors, including agriculture, disaster management, and urban planning, thereby enhancing societal resilience and economic stability.

5.4 Comparative Benchmarking Analysis

To provide a concise illustration of the potential benefits afforded by quantum computing versus traditional HPC systems, Table 3 compares headline values for energy consumption, daily usage, and approximate carbon emissions. The classical benchmark (e.g., the Frontier supercomputer) requires on the order of tens of megawatts (MW) to operate, reflecting both the computational workload and significant cooling overhead. By contrast, a superconducting quantum device typically consumes tens of kilowatts (kW), translating into markedly lower total energy requirements and, correspondingly, reduced carbon emissions.

While the figures below represent approximate or idealized values, they highlight a key sustainability advantage that quantum computing can offer as the hardware matures: potential exponential speedups in certain problem classes, combined with lower energy draw, can contribute substantially to global initiatives aiming to reduce the environmental impact of large-scale computation.

Metric	Classical Computing (HPC)	Quantum Computing
Energy Consumption	∼21 MW (e.g., Frontier)	∼25 kW (superconducting qubits)
Daily Energy Usage	504 MWh	0.6 MWh
CO_2 Emissions per Day	High	Significantly Lower
Computational Efficiency	Limited by Moore's Law	Potential for Exponential Speedup

Table 2: Approximate comparison of key energy and performance metrics between large-scale classical HPC and quantum computing architectures.

Metric	Classical Computing	Quantum Computing
Energy Consumption	High (e.g., data centers consuming significant energy annually)	Lower (e.g., photonic chips operating at room temperature)
CO_2 Emissions	Significant due to high energy use	Reduced owing to lower energy requirements
Operational Temperature	Requires extensive cooling systems	Potential for ambient operation
Environmental Impact	High, including substantial resource usage	Lower, with reduced resource requirements

Table 3: Comparison of Environmental Metrics: Classical vs. Quantum Computing

6 Conclusion

The integration of quantum computing into typhoon trajectory forecasting represents a transformative step toward enhancing predictive accuracy, computational efficiency, and sustainability. This study demonstrates that Quantum Parameter Adaptation (QPA) and Quantum-Train (QT) methodologies can significantly reduce the computational costs associated with high-resolution weather models while maintaining or exceeding classical performance levels. By reducing the number of trainable parameters through quantum-enhanced optimization, these approaches not only improve forecast precision but also lower energy consumption, reducing the environmental impact of large-scale simulations. Furthermore, the scalability of QT and QPA allows for seamless integration into existing meteorological infrastructure, ensuring widespread adoption without requiring substantial quantum hardware investments. Beyond typhoon forecasting, the principles established in this research pave the way for broader applications in climate modeling, energy optimization, and disaster risk reduction. As quantum computing technology continues to advance, its potential to revolutionize weather prediction and sustainability efforts will become increasingly evident, reinforcing its role as a key enabler of future climate resilience strategies.

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