Executive summary

Quantum computers promise to find solutions to certain classes of intractable problems more efficiently than a conventional computer. Namely, a quantum computer exhibits so-called quantum advantage for solving some hard problems over a classical computer. Here, we identify classically intractable Earth observation use-cases (EO UCs) of practical and strategic relevance, which can be computed efficiently on a quantum machine (computer). We provide our UCs ranked according to digital twin and green computing and explainable artificial intelligence paradigms. We define a quantum machine as a device that exploits quantum mechanical phenomena to perform a computation. This can be implemented in various ways, and quantum computers have many different technical implementations. These include quantum annealers, quantum analog simulators, and digital universal quantum computers, which each propose to tackle specific classes and forms of computationally hard problems. We will consider all three main categories, here listed in increasing order of generality and computational power:

1. **Annealers.** Quantum annealers are a kind of analog quantum simulator relying on the adiabatic theorem and mimicking an Ising Hamiltonian to solve quadratic unconstrained binary optimization (QUBO) problems such as satisfiability problems and combinatorial search problems. QUBO problems are solved by finding their global minimum over a given set of their candidate solutions (candidate states) by a process using quantum fluctuations. In adiabatic computing, noise- and error-tolerance are higher, which makes it hard to create entangled states, the main resource for quantum computational advantage over a conventional classical computer.
2. **Analog Quantum Simulators.** Analog quantum simulators are special-purpose devices designed to study quantum systems in a programmable fashion. They exploit superposition and entanglement to provide insight into specific physics problems mimicking the Hamiltonian evolution of the system. Analog quantum simulators are especially suited for simulating quantum physical systems, also, more general optimization is possible. As the quantum interactions between quantum particles are a built-in feature of quantum simulators, near-term quantum advantage is expected for the specific class of problems that they can describe.
3. **Digital Universal Quantum Computers.** The most powerful class of quantum machines that directly exploit superposition, entanglement, and wave-function interference and run quantum algorithms in a step-by-step procedure. A digital universal quantum computer can, in principle, solve some computable problems, with the additional advantage of up to exponential speed-up over classical computers. Digital quantum computers operate using quantum gates, logical operations on the basic quantum information primitives. These units are usually two-state quantum bits (qubits), but also continuous-variable (CV) approaches are under development. Qubits can be implemented using several different technologies, *e.g.*, superconducting, trapped ions, neutral atoms, or photonics, which all come with their unique strengths and weaknesses. There are some differences in algorithms between discrete and continuous quantum states, with CV approaches especially suited for, *e.g.*, sampling and regression tasks.

The three classes are in general suitable for different types of computational problems. Also, where different technologies can be applied to the same class of problems, performance will differ. The suitability of a particular problem for a specific quantum architecture is highly dependent on the implementation. Therefore, it is crucial to map and understand the relative strengths and suitability of the different approaches in order to gain quantum advantage as early and efficiently as possible. For all classes, we deliver their quantum development road-maps as provided by industry and academia over the time-frame of 3-5 to 15 years. For general-purpose quantum computers, we differentiate between Noisy Intermediate-Scale Quantum (NISQ) and Fault-Tolerant Quantum (FTQ) machines. NISQ machines have a limited number of error-prone qubits, while FTQ machines have multiple error-corrected qubits. It should be noted that quantum machines are not expected to replace conventional supercomputers, even in the long term. Quantum machines are suited for solving some specific problem classes. Thus, classical binary supercomputers will be required in practically all real-world high-performance computing work-flows of sufficient complexity. Traditional high-performance computing (HPC) and quantum computing is already being combined (HPC+QC).

Earth Observation (EO) methodologies involve optimization problems and artificial intelligence (AI) (i.e., machine and deep learning) to discover informative data and patterns in large-scale EO data-sets obtained from spectral sensors mounted on satellite and aircraft platforms. On the one hand, some optimization problems and AI techniques combined with big EO data-sets, that is, EO use-cases (EO UCs), are presently intractable problems for a conventional (super)computer alone. Thus, our objectives were:

- to identify intractable EO UCs for conventional supercomputers,
- to present quantum algorithms for those EO UCs promising potential quantum advantage in theoretical computational time (if available), an expressive power, and a computational capacity over conventional computers,
- to analyze the suitability of quantum machines for each EO UC,
- to select the most promising quantum machine architecture for each EO UC,
- to draw the quantum machine development road-map, and
- to provide a risk/opportunity analysis for quantum machines.

We emphasize that quantum machines promise to solve a certain class of hard computational problems faster than conventional machines. The hardness of the computational problems is measured from the perspective of computational complexity theory. Furthermore, we gained deeper insight into applying distinct quantum machines for climate and EO challenges. Quantum machines and their development road-maps are rapidly changing, and it is still not known which quantum machines and technologies will turn out to be the most efficient ones. Most likely, different implementations will excel at different problem categories, leaving us with several QC implementations also in the long-term. We note, hence, that this study is a first step toward deeper technical investigations for exploiting quantum advantage for EO and climate challenges. Toward quantum advantage, the next steps could be:

1. Designing quantum algorithms for EO and climate problems aligning with IBM‘s 100x100 challenge or other quantum technologies,
2. Investigating a special-purpose quantum machine for some hard computational EO task, such as a secure quantum learning model,
3. Identifying a solid EO problem that can be used to benchmark the performance of quantum and high-performance computing (HPC) infrastructure,
4. Assessing how to profit from combining quantum machines and HPC systems, and
5. Investigating optimal task sharing between quantum machines and an HPC system for computationally hard EO problems.

We identified four EO use-cases that may lead to the achievement of Quantum Advantage for Earth Observation (QA4EO) during the study. We ranked our use-cases based on quantum solutions for tackling climate change detection and mitigating climate change when considering their importance for making human-centered decisions.

Climate Adaptation Digital Twin HPC+QC Work-flow
The Climate Adaptation Digital Twin (Climate DT) aims to create a highly accurate digital model of the Earth to monitor and simulate the interactions between nature and human activity. The most resource expensive part in the present models of Climate DT is Computational Fluid Dynamics (CFD). In the medium-term, quantum computing and quantum machine learning can potentially be used to increase the accuracy of the models. Integrating quantum computing with supercomputers can lead to increased speed and accuracy in the ClimateDT workflow, which in turn will support decision making in Europe.

Uncertainty Quantification for Remotely-Sensed Data-sets
Satellite images and remotely sensed data-sets are limited in their label information and so small sized, whereas Deep Learning (DL) models demonstrate the advantage on large-scale datat-sets and are known as black-box models. In contrast, quantum learning models generalize better on small-scale datasets than DL models, and they promise to provide the uncertainty of their outputs, intractable for DL models deployed on a classical computer.

Quantum Algorithms for Earth Observation Image Processing
Current machine learning techniques for land-use classification are costly in terms of time and energy. There two possible approaches to solving this problem. The first one are Variational Quantum Algorithms. They are a class of quantum algorithms that is aimed at the application in the NISQ computing era. The second approach is to use quantum computers for a hybrid machine-learning approach utilizing an autoencoder for dimensionality reduction and a quantum algorithm powered by quantum annealer to reduce training costs.

Feature Selection and Feature Extraction for Satellite Hyper-spectral Imagery Data
The feature selection and extraction procedures have profound practical consequences, allowing for more effective data storage, transferring, reduction, and analysis. The hyperspectral data satellite data, with even hundreds of narrow spectral bands, provide an example of the area where utilization of the methods seems virtually unavoidable. The rich spectral information may surpass the needs of particular applications. Within the use case, we examined the possibility of applying quantum algorithms to improve the feature selection and extraction methods.

Quantum Resource Estimation for our Four QC4EO Use-Cases
The classical machine plays a lesser role in pre-processing classical data-sets, and we can feed many informative features to a quantum computer (less dimensionality reduction) as the number of error-free qubits of quantum machines increases. To execute the Parameterized Quantum Circuit (PQC) model on NISQ machines having 100 input qubits, we either reduce the data-set's features to at most 100 informative features or select most of the informative 100 features compatible with the input qubits by utilizing a classical machine. For quantum machines having more than 100 input qubits, we persevere more informative features when performing the dimensionality-reduction or feature selection technique in their features by using a classical machine. This paradigm of implementing quantum algorithms on quantum machines with 100 qubits and depth 100 is partly guided by the IBM's 100x100 challenge. Toward quantum resources required for executing our quantum solutions for four QC4EO challenges on digital quantum computers:

1. If our PQCs have 10^8 T-gates and five logical qubits, then we need 158,431 physical qubits (i.e., 9,375 state distillation qubits and 149,056 physical qubits) on the surface code distance of d = 25, and our QML models then take around 5 hours.
2. If our PQCs have three T-gate and five logical qubits, then we need 50,700 physical qubits (i.e., 14,400 state distillation qubits and 36,300 physical qubits) on the surface code distance of d = 11, and our QML models then take around 8.12×10^{-8} hours.
3. If our PQCs have one T-gate and five logical qubits, then we need 15,135 physical qubits (i.e., 14,400 state distillation qubits and 735 physical qubits) on the surface code distance of d = 7, and our QML models then take around 2.07×10^{-8} hours.

In addition, we present the scaling of physical qubits and surface (code) distance with respect to the gate error rate since PQC models require a logical error rate P_L of around 10^{-15} and a gate error p of 10^{-3} given the threshold error rate p_th of 0.57.

Present: The most advanced superconducting-based quantum computer in the market are limited to quantum models with a circuit depth of around five and a surface code distance of d=5 when considering error correction procedures. Hence, the main utility of QCs presently are to gain insights into quantum machines and developing methods and algorithms for more efficient QCs of the future.

In 3-5 years: There is a potential to implement proof-of-concept use-cases since quantum machines integrated with error mitigating procedures will have hundreds of qubits, reaching circuit depths of several hundred.

In 15 years: We probably can deploy our use-cases on several parallel quantum machines integrated with supercomputing systems, with each having hundreds or thousands of qubits, supporting circuit depths counted in thousands. Useful quantum computers will be already built and the potential use-cases are narrowed down.

Conclusion

Our objective was to identify at least three and at most five EO use-cases for quantum machines (QA4EO) in order of value for Earth observation. Quantum technology offers promising solutions to the challenges in Earth observation, making it more efficient and accurate. These advancements have the potential to improve disaster monitoring, climate analysis, and data analysis. Yet, assessing the future of quantum computers currently is a very difficult challenge. It is even a more difficult for tasks of practical importance since, today's existing quantum computers are unable to provide advantage even in artificially created tasks that suit these computers best. Quantum computers usefulness will depend on the particular application and at least the following technical parameters (see *Table I* for current parameters and *Table II for sizing quantum machines, and Figure I and Figure II for quantum machines roadmap*):

- number of qubits,
- qubit connectivity,
- single-qubit, two-qubit or multi-qubit gate fidelities,
- measurement errors,
- quantum system coherence time,
- execution time of operations reset, gate, and measurement,
- scalability of the quantum computing hardware platform,
- precision of control pulses,
- possibility to perform mid-quantum computing measurement and classical computing.

It is important to note, that in order to obtain quantum advantage as early as possible, software development is crucial. We need new quantum algorithms and quantum software, integrated with classical HPC infrastructure. Classical support software, *e.g.*, efficient compilers and noise mitigating post-processing methods need to be developed. In order to be able to provide an informed view about the future Quantum Advantage for the Earth Observation we recommend implementation of several studies that we believe should be performed to explore the applicability of future quantum computers for Earth observations. A research program lasting 3-5 years should allow the scientific community to identify pathways towards quantum computing advantage for Earth observations. Only after these studies, and similar, are finalized, a proper assessment of the future research directions can be made.

Table I: Primary technical parameters of some quantum machines

Parameters	SC	T.ions	Photonic	N.atoms	S.spin	NV	CPUs
Clock cycle	1MHz	1KHz	10Hz	1MHz	0.76MHz	1MHz	3GHz
Measurement	$660ns$	$300\mu s$	x	$200ms$	$1.3\mu s$	x	x
2-qubit gate	$34ns$	$200\mu s$	x	$< 100\mu s$	x	$700ns$	x
1-qubit gate	$25ns$	$15\mu s$	x	x	x	$9ns$	x
Readout fidelity	99.4%	97.3%	50.0%	99.1%	99%	98%	x
1Q fidelity	99.99%	99.99%	99.84%	99.83%	99.99%	99.99%	x
2Q fidelity	99.97%	99.9%	99.69%	99.4%	99.5%	99.2%	x

Table II: Quantum machines sizing based on data provided by industry and academia

Organizations	Locations	Technology	Current qubits	Projected qubits (3-5 years)
IBM	USA	superconducting	433	4,158
Google	USA	superconducting	73	100
IQM	FI	superconducting	20	54
USTC	CN	superconducting	66	100
AQT	AT	trapped ions	20	200
IONQ	USA	trapped ions	29	256
Xanadu	CA	photonic	216	216
USTC	CN	photonic	113	300
D-Wave	CA	superconducting-annealing	5,000	10,000
QuEra	USA	neutral atoms	256	1,000

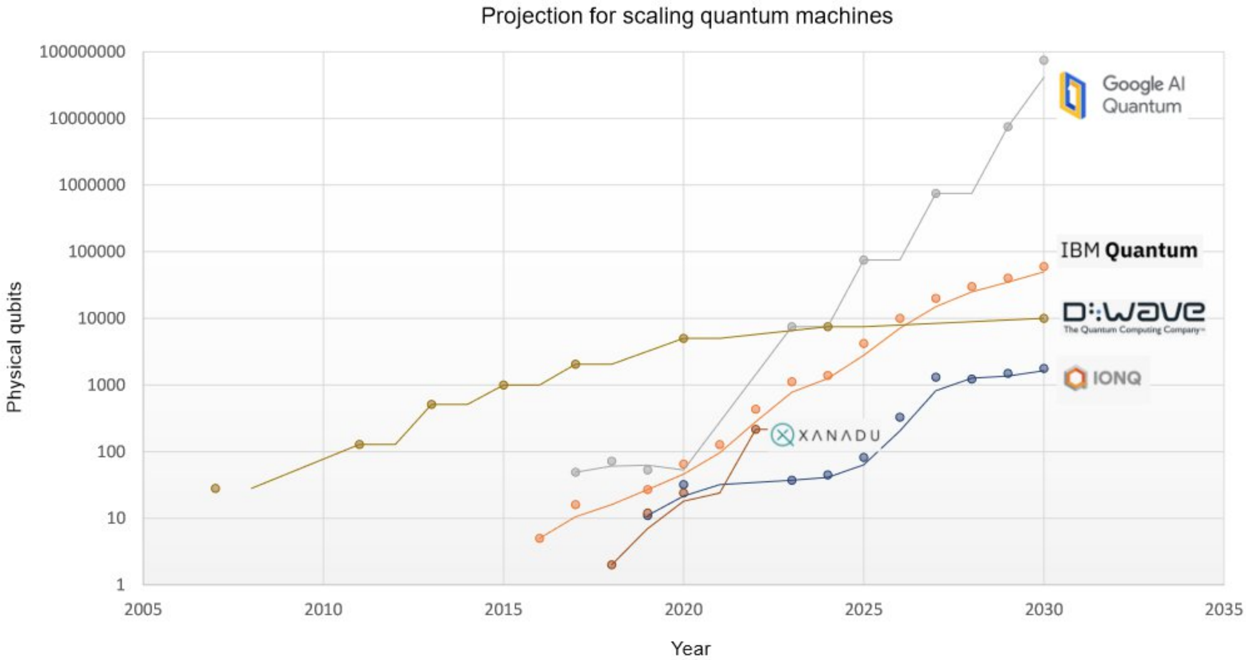

Figure I: Quantum machines roadmap of some organizations which provide open data for their quantum development projection.

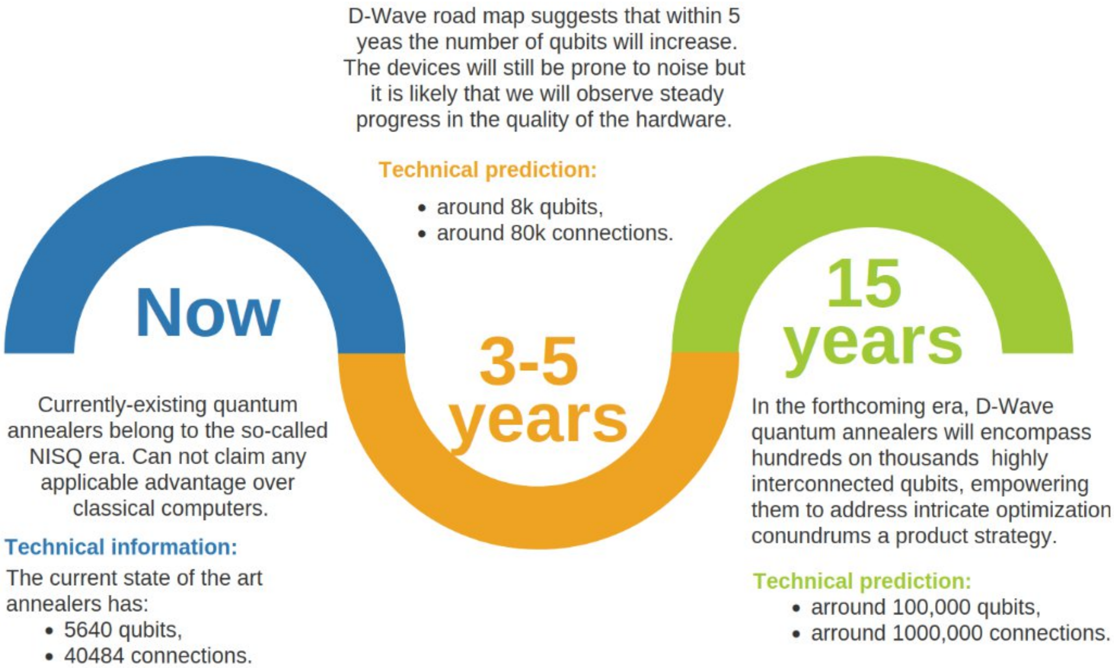

Figure II: D-Wave quantum annealer's roadmap