Climate Adaptation Digital Twin HPC+QC Work-flow

The Climate Adaptation Digital Twin (ClimateDT) is part of the Destination Earth initiative, where the goal is to develop a highly accurate digital model of the Earth in order to monitor and simulate the interactions between the natural environment and human activities. Through this, the effects of various natural phenomena and human actions on the climate can be studied, which will enable prediction of the effects of specific climate actions, aiding policy makers on how to best mitigate the effects of climate change.

When considering how to bring quantum advantage to the Climate DT, two aspects of the current climate models need to be considered:

1. Climate modelling is a "big data" problem. The number of grid points representing the atmosphere is counted in the hundreds of millions. Quantum computers are best suitable for problems with a moderate amount of both input and output variables.

2. Short wall-time for running Individual time-steps in the models. Propagation of one time-step is soon expected to be in the subsecond regime on the latest generation of supercomputers. Quantum calculations that provide a speed-up are expected to take at least seconds, and can therefore not accelerate current HPC calculations.

For quantum advantage, we need to consider the problem from a broader perspective. In the **medium-term**, advantage can be found by approaching the problem from new angles. In the **long-term**, with quantum processors integrated onto the same chip as classical processing it may be possible to execute useful tasks also on subsecond time-scales.

Table I: We presented the main quantum parameters of a superconducting quantum machine for our identified use-case [theoretical speculation, subject to change]. Here, theoretical speculation refers to gate error rate and gate fidelities, whereas the number of physical qubits are promised the quantum roadmap provided by industry.

	Present Day	3-5 years	5-15 years
Number of physical qubits	100	100-300	1,000
Circuit depth	5	100-300	1,000
Error rate/threshold error rate (p/p_th)	0.0149	0.0051	0.1823
Logical error rate	10^{-7}	10^{-13}	10^{-20}
1Q Fidelity	99.99%	99.99%	>99.99%
2Q Fidelity	99.97%	99.98%	>99.99%

The advantage of QC for climate modelling can be found in increasing the accuracy of the models, by including missing processes and features. One of the most promising ones is the inclusion of atmospheric chemistry such as aerosol-cloud interactions. These are highly challenging for classical systems to model for classical computers, but a near-perfect problem for quantum computers. Another manner for QC to improve climate modelling comes through the use of machine learning (ML) and artificial intelligence (AI). Classical ML/AI is introduced to climate modelling and computational fluid dynamics.

Here, quantum machine learning has potential advantages, such as possibly requiring less training data or providing more accurate results.

For quantum advantage, QCs with thousands of qubits with correspondingly low error rates (>99.99% fidelity) would be needed. This means that within **3-5 years**, incremental advantage, or at least a convincing prospect of advantage over purely classical methods relevant to Climate DT should be exhibited. Within **10-15 years**, quantum machines would have hundreds of thousands physical qubits, leading to true speed-up of climate models.

In order to gain quantum advantage as soon as possible, it is crucial for HPC and QC to work together. Existing workflows will have to be made quantum-ready. We need to identify the problems that are a bottleneck due to slowness or low accuracy on classical HPC. For this, specific research actions that bring experts on the present HPC climate models and quantum computing experts together is required.