AI-enabled MODEX and edge-computing over 5G for improving the predictability of water cycle extremes

Authors

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Focal Area(s)

The paper addresses focal area 1: data acquisition/assimilation enabled by AI and advanced methods including model-driven experiments, 5G, and hardware-related efforts involving edge computing.

Science Challenge

The interface between the land surface and the atmosphere is the driver of and is subject to many water cycle extremes [1]. The processes involved in the interface are highly heterogeneous [2]. For example, surface and subsurface biological response to extreme drought and flooding can precondition future fluxes from the soil-plant-atmosphere continuum [3]. An agile amorphous boundary layer–land surface network model is required to understand and improve the representation of the land surface–atmosphere interface in Earth system models (such as E3SM). This can be achieved only through an intelligent data acquisition and assimilation infrastructure. To that end, we envision an ambitious AI-enabled model-driven experiment (MODEX) and edge computing over a 5G network, with the aim of creating an intelligent data acquisition and assimilation framework that will advance the predictability of water cycle extremes.

Rationale

Achieving such predictability, especially over climate-relevant time periods, requires careful measurement and representation of water fluxes from the soil to the atmosphere and back to the soil (S2A2S) in models such as E3SM [4]. The S2A2S system is highly heterogeneous and nonlinear; it includes rainfall, soil and canopy evaporation, and vegetation transpiration. Many measurements that have these S2A2S systems are indirect, creating a barrier in traditional data assimilation and analyses to determine cause-and-effect relationships. This hinders the predictability of water cycle extremes such as droughts, which can cause the land to emit biogenic volatile compounds that can become aerosol precursors that impact the cloud formation, altering the extreme events on land. Moreover, latent and sensible fluxes influence atmospheric stability and are poorly sampled when heterogeneity due to land cover type or localized rainfall is present. The successful prediction of extreme events and an improved understanding of the impact of natural variability and anthropogenic influences on the regional and global water cycle require a better ability to collect and model the three-dimensional distribution of tropospheric water vapor and temperature and how these fields evolve with time.

Equally essential is a clearer understating of the fundamental processes driving precipitation occurrence and intensity—particularly when considering interactions between the land and atmosphere. For example, some studies of heterogeneous soil moisture have found that convective initiation occurs preferentially

DOI: https://doi.org/10.2172/1769672

DOE BER, AI4ESP 2021 #AI4ESP1008 (https://www.ai4esp.org)

over dry soils [5], whereas other studies have found occurrence preferential over wet soils [6]. Although evapotranspiration is generally correlated with incoming solar radiation, high temperature or high vapor pressure deficit can inhibit the water flux from vegetation. In order to improve scientists' ability to predict hydrological extremes, a far deeper understanding of these fundamental processes is essential.

Achieving this goal currently is limited by a number of factors, including (1) lack of dense observation networks to capture the full spatiotemporal spectrum and heterogeneity in the drivers of extreme events; (2) lack of synergistic use of instruments to maximize the information available from observations; (3) physical limitations of modern sensor technology, and the failure to utilize full data available from current sensors; (4) lack of low cost, miniaturized, easily deployable instrumentation; and (5) lack of AI-enabled model-driven experiments that perform targeted data collection based on different terrain and locations.

Narrative

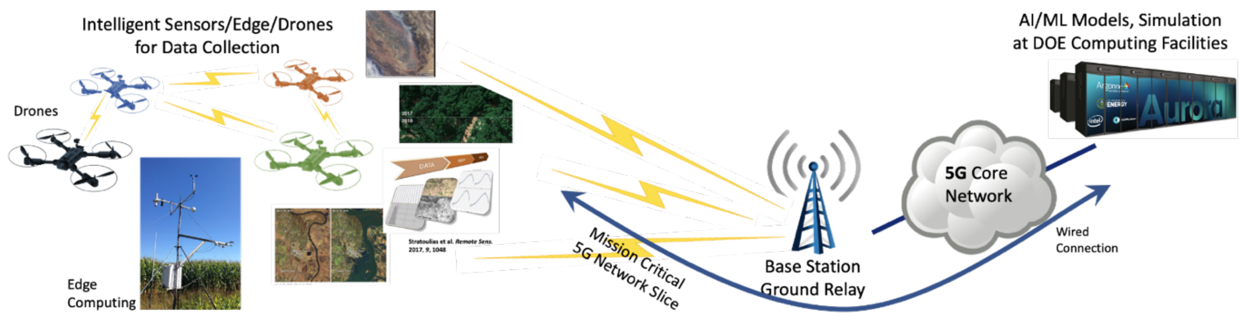

Fig. 1: AI-enabled model-driven experiment and edge computing over 5G network

Figure 1 shows our envisioned approach to address these limitations: an AI-enabled MODEX and edge computing over a 5G network. The features of our approach are (1) faster transfer of data between the measurement location and the processing center through ***5G network*** (as highlighted in the DOE ASCR 5G report [7]); (2) computational power to run real time simulations of the system under observation (digital twin) with a combination of instruments through ***DOE supercomputers;*** (3) the ability to optimize the observation capability in real time through ***edge computing***; and (4) capability to perform intelligent MODEX decisions at the computing facility and at the edge through ***AI/ML***.

The 5G network can be a potential game changer for advancing the water cycle's extreme predictability. The network enables a higher degree of programmability, which can deliver a wide range of new use cases, including (1) enhanced mobile broadband (eMBB), to support high-bandwidth data-driven use cases such as ecohydrology and tropospheric water vapor and temperature data collection; (2) ultra-reliable low latency communications (URLLC), to support mission-critical communications, for example remote control of autonomous aerial vehicles such as drones for targeted data collection; and (3) massive machine-type communications, to support dense deployments of sensor devices that enable the capture of the full spatiotemporal spectrum and heterogeneity in the drivers of extreme events. These new services will leverage the 5G network's revolutionary design of its software-defined core and transport networks and the radio access network that can support advanced wireless communication. With its 100x100 km footprint, highly heterogeneous land surface, and world-class instrumentation, ARM's Southern Great Plains (SGP) site is ripe for the implementation of a 5G-enabled observational network. By focusing on the boundary layer (lower that 7,000 feet), the network will avoid interfering with controlled airspace due to the nearby Vance AFB (we acknowledge the interagency complexities of autonomous sampling, but here we lay out the science incentives; the planned ARM's SEUSA site will be more appropriate).

Sensor instruments with edge AI/ML capabilities deployed in the field can help validate climate models emulated and simulated in DOE supercomputing facilities. Quantum sensors that leverage atoms and photons as measurement probes offer high-resolution measurements that were not feasible before. Utilizing AI/ML models running at the edge can provide high-level information, for example, detection of objects of interest and forecasting short-term events. This enables any appropriate changes on the sensing strategy in near-real time at the edge. For example, local weather changes (such as cloud cover) can be sensed by local edge devices and be used to assimilate the model for accurate short-term forecasts. For this scenario, it is crucial to build hybrid models of the physics and ML that help assimilate the data faster and maintain good accuracy. With the 5G network, this synchronization of sensing and heterogeneity significantly expands [8]: sensor platforms with 5G network can download a satellite image of the region to reinforce ML models for forecasting the hyper-local weather. Moreover, with the 5G’s peak minimum upload speed of 10 Gbps and minimum download speed of 20 Gbps and 300 Gbps-1Tbps+ for fixed wireless access, it is feasible to stream 4K–8K videos directly from the edge sensors and drones to DOE supercomputing facilities. Such high resolution of sensor measurements can significantly improve data assimilation and eventually the accuracy of climate/weather models to predict extreme water cycles. Moreover, well-validated climate models may guide the ML models and sensor platforms with macro-level information available only in the climate models.

MODEX enabled by 5G-connected edge computing will also drive agile remote sensors such as drones, steerable cameras (both visible and thermographic), Doppler, quantum sensors, and micropulse Lidar and radar. The autonomous sensors and the agile sensors will be used in coordination, linking point measurement to volumetric measurements. Forward models (i.e., instrument simulators, including AI emulator based) will link high-resolution model parameters to remotely sensed irradiances, signal-to-noise ratios, and radar parameters such as reflectivity factor. Drones can operate as flying mobile terminals within the 5G network to perform a plethora of tasks involving sensing, communications, and data analysis. The 5G's specifications for eMBB and URLLC allow these applications to perform efficiently with both edge and supercomputing working in tandem. For example, if an adjoint LES model predicts convective initiation along an assimilated dry line over the SGP site, the stationary agile sensors can be directed to sample along this line, and autonomous in situ sensors could be directed to probe the area. As clouds initiate and deepen, the amorphous observatory can be reconfigured. This requires highly novel, adaptive, and programmable coordination among edge computing, 5G communication, and models running on DOE supercomputers.

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