Artificial Intelligence-Enabled Digital Twin for U.S. Cities

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Workshop on Developing an Artificial Intelligence-Enabled Digital Twin using Chicago as a Benchmark

What:

Over 50 participants — including national laboratory researchers, academic scholars, industry representatives, and stakeholders from the City of Chicago — convened in person and online to assess the readiness and potential of an Artificial Intelligence–Enabled Digital Twin (AIDT) for urban systems, with the Greater Chicago area serving as the benchmark location. The workshop underscored that the Chicago Urban Integrated Field Laboratory provides an unparalleled testbed for developing and validating urban DTs — combining dense, multi-scale observations, advanced physics-based and AI modeling capabilities, and strong stakeholder and industry engagement. Discussions highlighted available datasets, AI architectures for high-resolution, multipurpose urban DTs, key applications, and near- and long-term priorities for scaling this framework within Chicago and to other U.S. and global cities.

When:

July 29–30, 2025

Where:

Argonne National Laboratory, Lemont, Illinois

Keywords:

Urban systems, AIDT, energy consumption, urban buildings, multi-scale models, multi-scale observations

The National Academy of Sciences, Engineering and Medicine (NASEM 2023) define a digital twin (DT) as comprising two key elements: (1) modeling and simulation to create a virtual representation of a physical counterpart, and (2) a bidirectional interaction between the virtual and the physical systems. This bidirectional interaction forms a continuous feedback loop in which real-world observations update the virtual model, while model outputs inform or drive changes in the physical system. The resulting insights support timely, evidence-based decision-making. In the weather–resiliency domain, such synchronization is essential for capturing coupled processes between the built environment, natural systems, and the atmosphere (Dale et al. 2023). While DTs have been in development for decades, the integration of artificial intelligence (AI) has ushered in a new era of AI-enabled DTs (AIDTs), capable of real-time

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operations and deep integration with human-environment, and governance data to support actionable science and stakeholder decisions (Huang et al. 2022). AIDTs retain the foundational features of DTs but augment them with AI to accelerate model–data fusion, enable easier multi-sectoral integration with physics models, enhance predictive skill, quantify uncertainty, and enable adaptive sensing or operational control (Huang et al. 2022). In urban weather applications, this integration links physics-based numerical models with AI foundation models for the earth system (Nguyen et al. 2024a, b), trained using high-resolution simulations and enhanced with generative approaches for scenario exploration—producing rapid, high-resolution, and uncertainty-aware forecasts that directly inform decision-making (Dale et al. 2023).

Recent initiatives illustrate the potential of these concepts at scale. The Destination Earth (DestinE) program (https://destine.ecmwf.int), led by the European Commission, is creating high-precision DTs of the Earth—focused on weather-induced extremes and multi-decadal, weather-resilient adaptation strategies—to deliver interactive, city-scale hazard and impact forecasts via AI-augmented Earth system models. In Southeast Asia, Virtual Singapore (Ignatius et al. 2019) integrates detailed three-dimensional (3D) urban morphology, real-time sensor data, and scenario modeling to support applications such as heat mitigation, flood management, and energy planning. In the United States, efforts to build operational urban weather–climate AIDTs are still at an early stage. However, emerging research highlights how combining newly developed infrastructure with real-time meteorological inputs, AI-driven foundation models, and advanced analytics can enhance both immediate hazard response and long-term adaptation planning. Fully realizing this potential will require integrated urban testbeds where physical observations, high-resolution models, and AI workflows are co-developed, evaluated, and iteratively refined under real-world conditions—creating a critical bridge from research prototypes to sustained, operational capabilities.

To build momentum for the AIDT vision in an operational urban/energy infrastructure resilience context, the Chicago Urban Integrated Field Laboratory (Chicago-IFL) has led a multi-institutional, interdisciplinary, and international effort to link technological advances with local urban needs. The July 2025 hybrid workshop at Argonne National Laboratory served as a platform to initiate the development of a fast, expandable and accurate system for conducting urban-scale multi-sectoral analysis for developing insights into data needs,

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developing virtual test beds, and supporting infrastructure resilience, in particular the energy sector.

The dialogue was grounded in current Chicago-IFL products and capabilities (Chen et al. 2025; Nesbitt et al. 2024; O'Brien et al. 2024a-d; Pal et al. 2024, 2025; Raut et al. 2024 Tuftedal et al. 2024) and Argonne's weather-focused AI foundation models (Nguyen et al. 2024a, b). These products and capabilities included: (1) Street- and city-scale model development and benchmark simulations that better characterize urban impacts — such as building effects and human activities — on thermal comfort and energy consumption; (2) Multi-scale measurements spanning soil, trees, the near-surface atmosphere, and atmospheric profiles, collected through fixed sensor networks and field campaigns that, for the first time, comprehensively capture urban canyon and urban-lake interactions; (3) An AI workflow built on Argonne's weather-focused AI foundation models and deployed on the Aurora Exascale system, targeting subseasonal-to-decadal scale forecasting; and (4) a roadmap outlining near-term actions and a long-term vision for realizing an AIDT for urban systems — beginning with Chicago and aiming to scale across the U.S. The workshop featured individual presentations, panel discussions, parallel breakout sessions, and hands-on activities exploring various AI architectures and workflows.

Industry and stakeholder Perspectives on AIDTs

Traditional urban planning often relies on regional-scale weather datasets—typically sourced from airport observations—which fail to capture the complexity of urban microclimates, such as heat islands, wind corridors, and shading effects. An AIDT that integrates across physical and human-environmental domains can overcome these limitations by integrating multi-scale data to provide high spatial granularity and sector specific outcomes. This enables planners and designers to assess how large-scale environmental changes impact specific locations and to optimize building design — such as insulation, wind loading, and shading — tailed to local conditions. Additionally, there remains limited understanding of emissions from both construction and operations at the city scale, especially for infrastructure, despite the potential for city populations to double in the coming decades. AIDTs can help fill this gap by quantifying citywide energy use and emissions, supporting optimal urban density planning, and improving resilience to extreme meteorological and hydrological events. On the other hand, stakeholders such as utilities and emergency managers need tools for both

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reliability (short-term operations) and resilience (long-term planning). AIDTs can support both by integrating diverse datasets, enabling situational awareness, and testing infrastructure investments virtually to guide capital spending decisions. With many government bodies involved in urban infrastructure (schools, parks, water systems, etc.), AIDTs can act as a "clearing house" to break silos, centralize planning, and visualize city assets in an accessible, movie-like format for communication and decision-making. Historical urban planning initiatives, such as the Plan of Chicago (Burnham and Bennett 1909), although static in nature, have demonstrated the transformative power of long-term, visionary design. AIDT can serve as a modern living digital master plan – responsive to involving urban environments, development pressures, and weather disturbance risks. Enhanced by AI, the AIDTs enable rapid iteration, scenario testing, and uncertainty-aware modeling, bridging the gap between static master plans and the dynamic realities of future urban systems.

A Chicago Testbed: Multiscale Datasets for Urban Data-Bench

The workshop highlighted how the Chicago-IFL initiative uniquely enables the development of urban AIDTs by integrating state-of-the-art multi-scale modeling with equally advanced multi-scale observations.

Street- and City-scale modeling effort through Chicago-IFL: The team developed ultra-high-resolution 3D urban geometry datasets—such as detailed height maps of trees and buildings (Li and Sharma, 2022) and the Global Building heights for Urban Studies (Kamath et al., 2024)— that resolve building and vegetation characteristics at the meter scale. These inputs refine parameters in mesoscale models like the Weather Research and Forecasting (WRF) model, improving the accuracy of the Building Effect Parameterization (BEP). Enhancements include refined estimates of tree fraction by local climate zone, tree height, building height/width, street width, and the fractions of various building heights. Compared to default urban datasets, which often overestimate tall-building fractions and overlook vegetation, these refined inputs offer a far more realistic representation of urban form. In addition, a new multi-layer mixing-length turbulence closure (Fytanidis et al. 2025) — informed by building-resolving, street-scale large-eddy simulations (LES) and literature data— captures vertical turbulence variability across low-, mid-, and high-rise environments. Implemented into BEP and tested in city-scale WRF simulations at 500-m and 80-m resolution, the new scheme improves predictions of near-surface temperature, humidity, and wind, while better resolving building-induced wake effects and wind variability in downtown Chicago. The

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simulation also enhanced the calculation of the Richardson Number, using virtual potential temperature and vertical wind shear to assess atmospheric stability more accurately. Additionally, the model incorporates the role of urban trees in modulating shortwave radiation and surface energy balance.

The modeling capability ranges from month-long, 500-m resolution city-scale simulations to real-time, 80-m resolution WRF-LES street-scale forecasts. Using these advancements, the team has conducted multi-day to month-long simulations to investigate urban expansion, sensitivity to urban parameters, and squall line development from thunderstorm in the Chicago region. The 500-m simulations generate tens of thousands of output images, each with approximately 160,000 grid cells per vertical level, across more than 50 levels. Additionally, a real-time WRF-LES system at 80-m resolution was developed to further enhance street-scale modeling capabilities. These outputs include thermal comfort index (Martilli et al. 2024) and hourly estimates of air conditioning energy consumption at each grid cell. Furthermore, the team is on track to deliver a realistic model for simulating urban hydrologic, hydraulic, and citizen responses to heavy precipitation events at the street scale using the Storm Water Management Model. The workshop also introduced the Chicago Social Interaction Model (ChiSIM) framework (Macal et al. 2018), which has been evolving its DT concept since before its integration into Chicago-IFL. Recent enhancements incorporate electric sector infrastructure, enabling the model to assess the impacts of extreme events on electric infrastructure, and to estimate neighborhood-scale demand and consumption of electricity.

Measurement effort through Chicago-IFL: The workshop provided an overview of Argonne’s multi-scale observational efforts, encompassing both long-term monitoring and intensive observation periods (IOPs) conducted in 2024 and 2025. These IOPs focused on understanding urban canyon dynamics and city-scale flooding. A wide array of sensing technologies has been deployed across street- to city-scale domains to support urban weather modeling and validation. At the street scale, the team implemented sap sensor networks and multi-function remote sensing nodes capable of monitoring solar radiation, air temperature and humidity, multi-depth soil temperature, ground energy exchange, and water quality. High-resolution measurements of trace gases and aerosols were collected at the University of Illinois Chicago campus — located less than two miles from Chicago downtown skyscraper — to benchmark aerosol model performance. A 15-site Micronet recorded meteorological variables and rainfall at minute-scale resolution, providing crucial data for modeling urban heat and flood. Additional infrastructure included a long-term flux tower and the Argonne Deployable

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Mast, both used to observe energy fluxes and precipitation for model evaluation. Local precipitation data were further supplemented by CoCoRaHS community rain gauges. At the mesoscale and city scale, 3-hourly atmospheric soundings and lidar systems were used to collect vertical profile data. City-scale wind and turbulence measurements, including autonomous gust sensing, were carried out to validate model simulations. Early results from a three-week autonomous sensing campaign demonstrated successful, continuous data collection and contributed to improved inputs for city-scale turbulence modeling. The workshop also highlighted the use of AI agents for adaptive scanning, such as Waggle-based plugins that enable event-triggered observations — for example, during lake breeze events. This edge-computing platform enhances real-time responsiveness and situational awareness, allowing the observational network to dynamically target evolving weather and environmental phenomena. By integrating the most detailed urban morphological datasets available, an improved physics-informed turbulence parameterization, street-to-city scale modeling systems, and AI-enhanced, multi-platform observational networks, the Chicago-IFL positions the city as the premier U.S. testbed for developing and validating operational urban AIDTs. Chicago's data richness, advanced modeling infrastructure, and strong stakeholder engagement enable rapid iteration, scenario testing, and uncertainty-aware decision support—transforming the DT concept into a living, evolving urban master plan for resilience and adaptation.

AI-architecture and scalable workflows for urban AIDT.

While many machine learning architectures—such as convolutional neural networks, transformers, and graph neural networks—are available, the workshop emphasized that effective AIDTs must be purpose-driven and tailored to specific decision contexts and available resources. The AIDTs should be grounded in scientific rigor, with core principles including reproducibility, uncertainty quantification, model validation, and data provenance. Within this framework, the workshop introduced a key component of Argonne's latest Earth System Foundation Model: a scalable and generative weather model, build on the Swin Transformer and trained on 0.25° European Centre for Medium-Range Weather Forecasts atmospheric reanalysis of the global climate, version 5. This model delivers high-resolution sub-seasonal to seasonal forecasts with substantial gains in computational speed and energy efficiency. Leveraging innovations such as pressure-weighted loss functions, sequence-window parallelism, and weather-specific embeddings, the model was successfully scaled to 37 billion parameters across 90% of Aurora — one of the world's largest supercomputers. It also marks

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a shift from deterministic to probabilistic forecasting by incorporating diffusion-based generative approaches, thereby enhancing uncertainty representation for forecasts extending beyond traditional operational windows. Alternative modeling strategies — such as GraphCast (Lam et al. 2023), Fourier Neural Operators (Kurth et al. 2023), and diffusion-based data assimilation (Huang at al. 2024) — were also explored to enhance spatial reasoning and to incorporate the observational data from Chicago-IFL. Building on numerical model development, high-resolution simulations, observational campaigns, and AI tools supported by Argonne's high-performance computing infrastructure, the team demonstrated readiness to initiate an urban AIDT prototype for the Chicago region. This prototype will integrate urban weather, infrastructure, energy use and social components, serving as a scalable blueprint for deployment in other cities.

Finally, the presentation stressed the importance of interpretability, explainability, and user trust in AIDT systems. These priorities align with the National Institute of Standards and Technology's AI Risk Management Framework (NIST 2023) and best practices from National Science Foundation's (NSF) AI Institute for Research on Trustworthy AI in Weather, Climate, and Coastal Oceanography (AI2ES) best practices (McGovern et al. 2022, 2024). A modular, reproducible software framework was shared to support the scalable, transparent, and trustworthy development of urban AIDTs.

Leverage broader resources and initiate AIDT training.

While Chicago-IFL has focused on street- and city-scale modeling and measurements, large-scale DOE efforts at regional and global levels offer critical opportunities to advance AIDT development and scale applications to global urban contexts. Conversely, regional and global modeling initiatives can benefit from Chicago-IFL by improving their representation of urban processes. Several DOE-supported modeling programs can be directly leveraged to support the AIDT vision: (1) The regionally refined Simple Cloud-Resolving Energy Exascale Earth System Model (E3SM) Atmosphere Model on GPUs enables convection-permitting simulations over targeted regions and at global scale (Donahue et al. 2024); (2) The Coastal Observations, Mechanisms and Predictions Across Systems and Scales–Great Lakes Modeling project produces long-term, convection-permitting simulations using a coupled atmosphere–land–lake model with integrated 3D lakes hydrodynamics (Kayastha et al. 2023); (3) E3SM and other Earth system models incorporate ocean, sea ice, biogeochemistry, and human systems (including energy and socioeconomics) via tools such as the Global Change Analysis

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Model (e.g., Le Page et al. 2016), providing training data for globally scalable urban AIDTs. Additionally, DOE's extensive computing resources and scientific expertise are essential for advancing both physics-based and AI-driven urban environmental modeling. Continued investment in research is crucial to better understand how urban components interact and influence resilience. This includes enhancing system coupling across Earth system and energy domains, bridging multiple spatiotemporal scales, and expanding observational sensor networks to strength the Model-Observation-Data Integration Experiment framework.

The workshop established working groups dedicated to data processing, model training, and AI model evaluation. The team agreed to initiate training using Argonne's Earth system foundation modeling framework, with an emphasis on much higher spatial resolution (e.g., hundreds of meters) over the Great Chicago region. This effort leverages existing high-resolution datasets — such as the High-Resolution Rapid Refresh model (Dowel et al. 2022) —along with Chicago-IFL model outputs and observations, within a data assimilation framework (e.g., Huang et al. 2024). The goal is continuous refinement through integration of additional observational, energy, and building datasets, ultimately delivering an adaptive, city-specific AIDT prototype that can be scaled to other regions.

Main takeaways

(1) There is strong public, private, and educational interest in developing an AIDT for

Chicago to serve as a prototype and testbed for broader deployment across U.S. cities.

(2) The Chicago-IFL has produced multi-scale urban simulations and observations, framing a critical foundation for training and validating AIDTs tailored to Chicago and adaptable to other urban environments.

(3) Building the foundation model and expanding it into an AIDT requires close, integrated collaboration between domain scientist and software engineers. Both areas of expertise are already present within the established team.

(4) Large-scale efforts across the DOE national laboratories, universities, and the broader academia provide complementary modeling, data and capabilities that can be leveraged to accelerate the development of urban AIDTs for both U.S. and global cities.

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Data Availability Statement.

N/A

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