BULGARIAN ACADEMY OF SCIENCES

SPACE RESEARCH AND TECHNOLOGY INSTITUTE

ADVANCED COMPUTATIONAL APPROACHES FOR DATA-DRIVEN AND INTELLIGENT MODELING OF ATMOSPHERIC PROCESSES

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ABSTRACT: *A review of contemporary methods for intelligent modeling and analysis of atmospheric processes, focusing on atmospheric pollution and EO data extraction for simulations. ESDTs as dynamic virtual replicas for simulation and prediction. System dynamics for complex interrelationships. Monte Carlo for uncertainties in 'what-if' scenarios. Genetic algorithms for optimization, genetic programming for interpretable dependencies. Comparison of NNs and ELMs for accuracy and efficiency. LLMs (e.g., NASA Galileo, IBM TerraMind) for heterogeneous EO data integration. Methods support processingand interpretation of satellite/ground observations.*

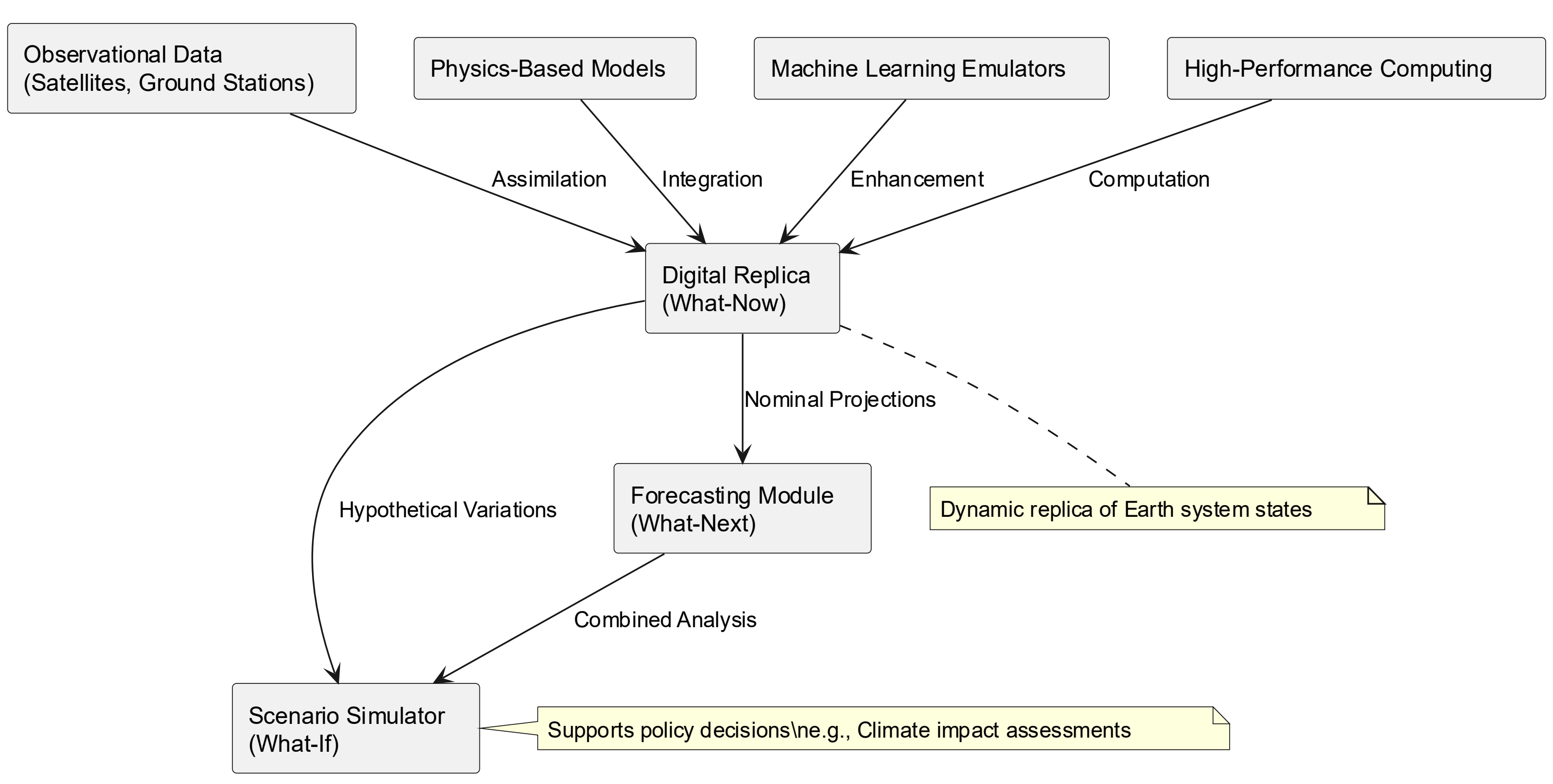
1. Introduction

Atmospheric processes—including air quality dynamics, climate variability, and pollutant transport—are inherently complex, nonlinear, and subject to uncertainties. Accurately modeling and forecasting require advanced computational methodologies integrating EO data from satellites (e.g., MODIS, Sentinel-5P) and ground systems. We review progress in intelligent approaches: ESDTs, system dynamics, Monte Carlo simulations, NNs, ELMs, GAs, GP/symbolic regression, and LLMs. These address data integration, interdependencies, and adaptation to environmental conditions.

2. Key Methods

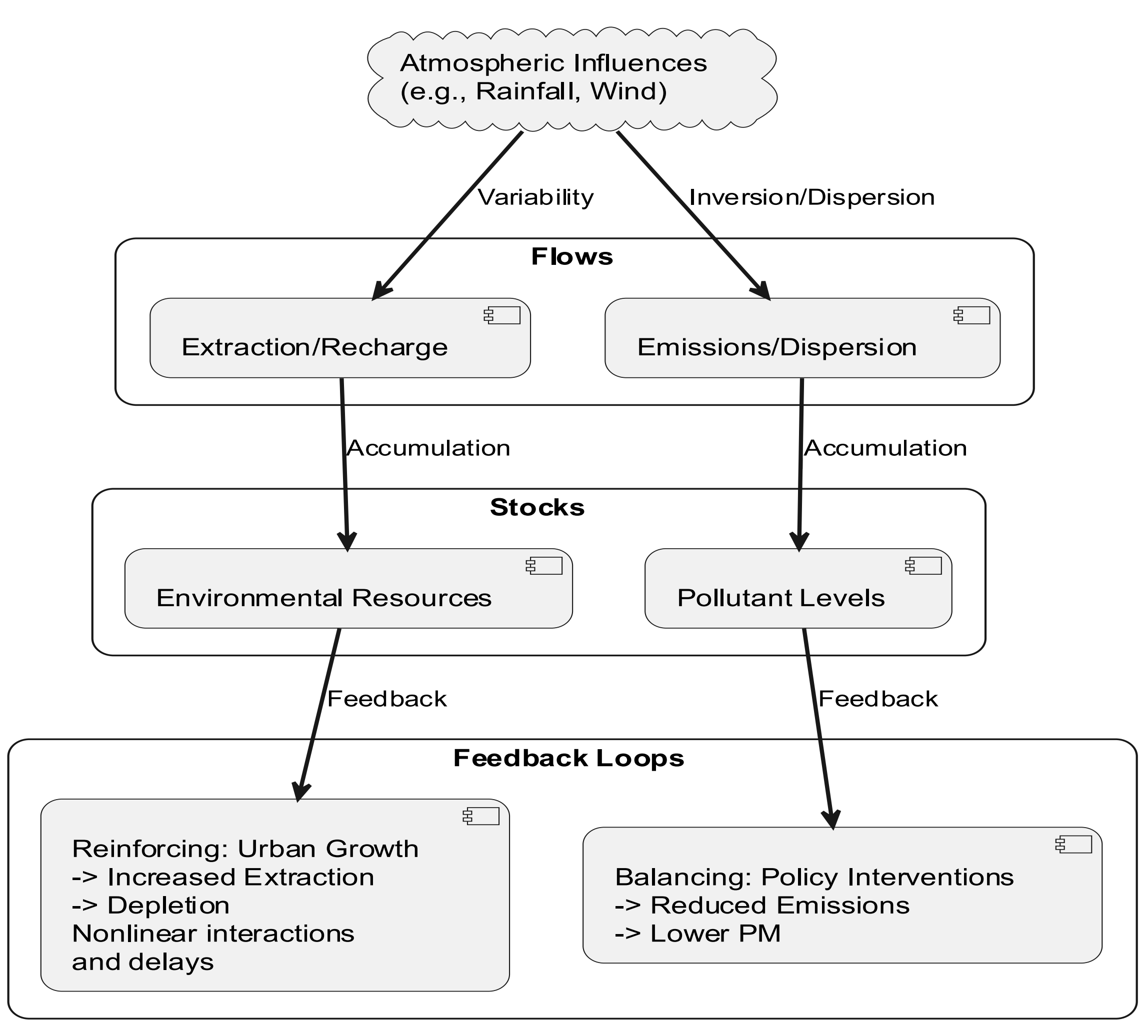
Earth System Digital Twins (ESDTs)

- Dynamic virtual replicas integrating observational data and models for replication, prediction, and simulation.
- Key features: Multi-source data integration, multiscale modeling, hybrid approaches.
- Applications: Planetary boundary layer dynamics, aerosol transport, urban air quality in Sofia.



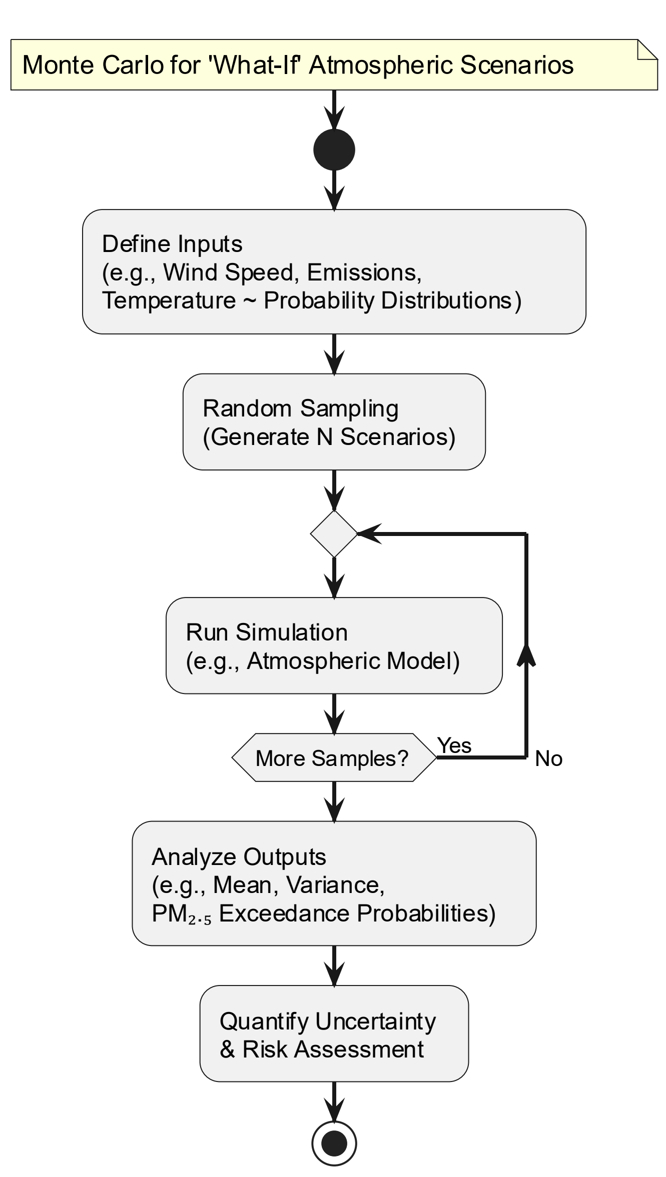
System Dynamics Modeling

- Computational methodology using feedback loops, stocks, flows, and delays.
- Applications: Pollutant dispersion, hydrological cycles, long-term policy interventions.



Monte Carlo Simulation

- Statistical method using random sampling to model uncertainties.
- Applications: Air quality forecasts (e.g., $PM_{2.5}$ levels), probabilistic climate projections, risk assessment.



Neural Networks and Extreme Learning Machines

- NNs: Learn nonlinear relationships; CNNs for satellite imagery, LSTMs for sequences.
- ELMs: Fast, non-iterative training for real-time tasks like $PM_{2.5}$ nowcasting.

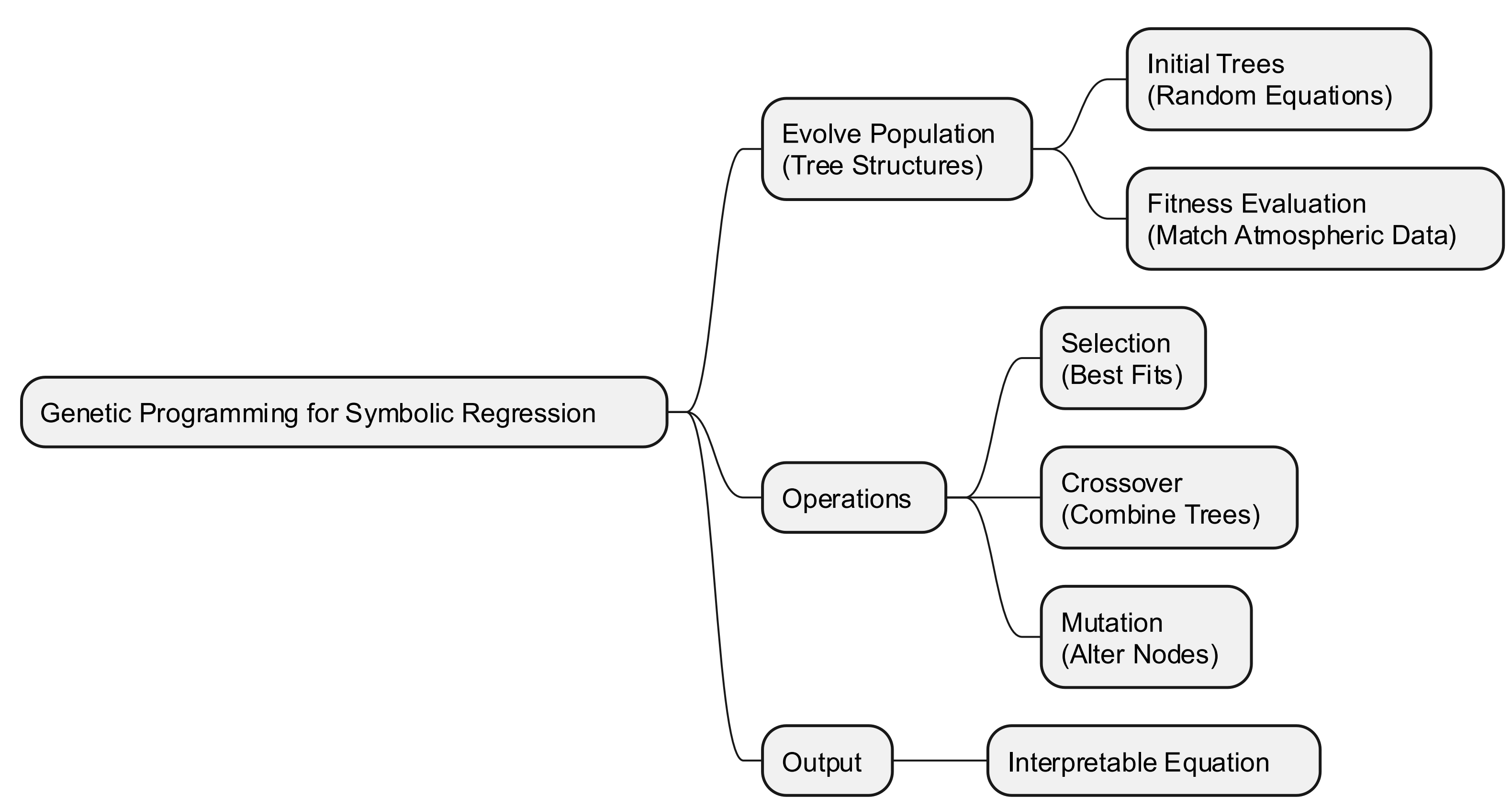
Aspect	Neural Networks (NNs)	Extreme Learning Machines (ELMs)
Predictive Accuracy	High (e.g., outperforms ELMs in deep feature tasks; RMSE ~0.05 for nonlinear dynamics)	Comparable or better in fast time-series (e.g., superior in wave forecasting benchmarks)
Training Time	Slow (iterative; hours–days for large datasets)	Fast (analytical; seconds–minutes, 1000x speedup over backprop)
Real-Time Efficiency	Limited by computation; suitable for offline	High; ideal for streaming/onboard processing
Suitability for Atmospheric Applications	Complex simulations (e.g., radiative transfer)	Operational nowcasting (e.g., aerosol visibility)

Genetic Algorithms

- Adaptive optimization inspired by natural selection.
- Applications: Parameter tuning for NNs/ELMs, satellite scheduling for EO data collection.

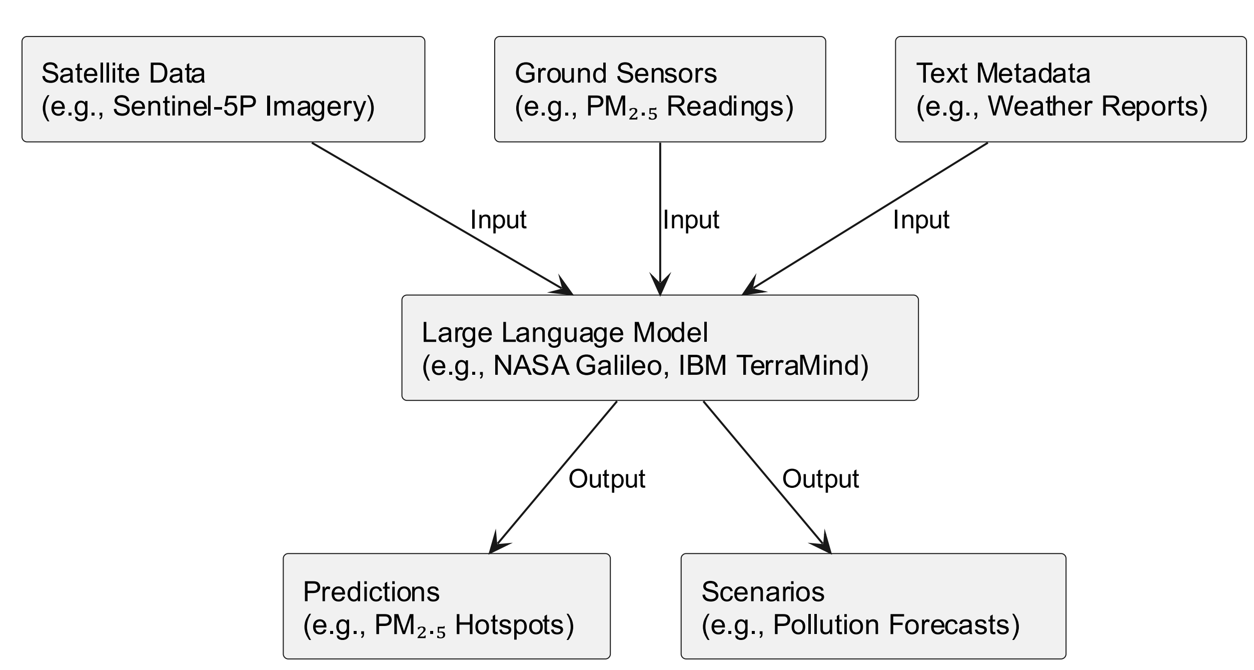
Genetic Programming and Symbolic Regression

- Evolves programs/equations for interpretable models.
- Applications: Deriving equations for pollutant dispersion (e.g., $PM_{2.5}$ decay).



Large Language Models

- Multimodal models (e.g., IBM TerraMind, NASA Galileo) for EO data fusion and querying.
- Applications: Natural language interaction, scenario modeling for air quality.



Applications and Implications

- Synergies: GAs optimize NNs/ELMs; Monte Carlo enhances ESDTs; LLMs integrate outputs.
- Hybrid frameworks improve accuracy and applicability for atmospheric modeling.
- Air Quality Forecasting: Predicts $PM_{2.5}$, ozone using NNs, ELMs, and LLMs, validated with AIS data.
- Climate Risk Assessment: Models wildfire smoke and urban heat islands via ESDTs and Monte Carlo.
- Disaster Preparedness: Supports policy with system dynamics and GAs for emission controls.
- EO Integration: Leverages Sentinel-5P, MODIS, and TROPOMI for real-time insights, enhancing environmental management and public health in regions like Sofia.