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Research Paper Title :Earth System Foundation Models for Predicting Extreme Climate Events Through Integrated Satellite, Oceanic, and Land-Surface Intelligence

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Abstract:

This study investigates the scientific and operational potential of Earth system foundation models for anticipating extreme climate events through the joint assimilation and representation of atmospheric, oceanic, and land-surface information. The manuscript develops a rigorous synthesis framework built on real observational and reanalysis data sources, including ERA5, SMAP, NOAA OISST v2.1, GPM IMERG, MODIS surface products, and the NOAA IBTrACS archive. Rather than treating weather, ocean, and land processes as isolated forecasting domains, the proposed framework formalizes extreme-event prediction as a multiscale sequence-learning problem in which precursor signals propagate across coupled geophysical subsystems. Particular attention is given to rapidly intensifying tropical cyclones, compound flood events, and heat-related marine and terrestrial extremes, because these hazards expose the limits of conventional single-domain models and the benefits of cross-sphere intelligence.

The methodological contribution consists of Earth system intelligence pipeline that integrates heterogeneous spatial resolutions, temporal frequencies, and physical variables into a unified tokenized representation suitable for transformer-based foundation modeling. The paper specifies real data collection procedures, harmonization rules, loss functions, and event-centric evaluation protocols using track error, anomaly reconstruction, rare-event likelihood, and warning-skill diagnostics. To maintain realism, the empirical section relies on documented public data and published benchmark outcomes from peer-reviewed or official sources rather than synthetic examples. Comparative evidence from Aurora, Pangu-Weather, GraphCast, and related systems is interpreted alongside real extreme-event indicators from Hurricane Otis (2023), the Pakistan floods (2022), and North Atlantic marine heat anomalies (2023).

The results indicate that Earth system foundation models achieve meaningful gains when the representation space is informed by coupled oceanic and land-surface precursors rather than atmospheric state alone. Published evidence shows that Aurora exceeded operational baselines on 92% of high-resolution weather targets, 86% of ocean-wave targets, 74% of air-quality targets, and 100% of evaluated tropical-cyclone-track targets, while Pangu-Weather reduced 3-day and 5-day tropical-cyclone direct-position errors relative to ECMWF-HRES. Case evidence further shows that extreme events consistently emerge from interacting anomalies in sea-surface temperature, moisture availability, antecedent soil state, and circulation structure. Accordingly, the paper concludes that Earth system foundation models offer a credible pathway toward next-generation early-warning systems, provided that uncertainty quantification, interpretability, and equitable operational deployment remain central to future research.

Keywords: Earth system foundation models; extreme climate events; satellite intelligence; ocean-atmosphere coupling; land-surface intelligence; tropical cyclone prediction; flood forecasting; climate AI

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1. Introduction

1.1 The rising need for integrated extreme-event intelligence

Extreme climate events increasingly emerge as coupled Earth system disturbances rather than isolated meteorological anomalies. Rapidly intensifying tropical cyclones, compound floods, coastal heat extremes, and drought-to-fire cascades are all shaped by interactions among atmospheric circulation, sea-surface thermal structure, antecedent land moisture, vegetation state, and basin-scale teleconnections. Conventional operational workflows remain highly capable, yet they are often organized around discipline-specific numerical components, observational pipelines, and hazard products. This fragmentation can limit the capacity to identify precursor structures that evolve across subsystem boundaries before an event becomes operationally obvious.

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Earth-observing satellites, ocean reanalyses, and land-surface products have transformed the empirical basis for hazard anticipation. Global reanalyses such as ERA5 provide temporally consistent atmospheric state estimates; microwave and thermal sensors constrain soil moisture, surface temperature, and cloud properties; ocean temperature analyses resolve persistent warm anomalies that modulate cyclone intensification and marine heatwaves; and archives such as IBTrACS supply event-resolved best-track records for evaluation. The scientific challenge is therefore no longer simple data scarcity. The more pressing issue is how to convert heterogeneous, multiresolution observations into coherent predictive representations that retain physically meaningful cross-domain dependencies.

This study situates extreme-event prediction within that representation problem. It argues that Earth system foundation models offer a strong conceptual and methodological response because they are designed to learn transferable structure from diverse geophysical archives before being adapted to specific forecasting tasks. In contrast with narrow task-specific models, a foundation-model approach can encode recurrent multiscale relations among atmospheric dynamics, ocean heat content proxies, and land-surface memory. Such a formulation is especially relevant

for extremes, where seemingly moderate anomalies in one subsystem can become highly consequential when aligned with preconditioning in another.

1.2 Foundation models in weather and climate science

Recent advances in artificial intelligence have altered the methodological frontier of weather and climate prediction. Data-driven systems such as Pangu-Weather and GraphCast demonstrated that global forecasting models trained on reanalysis data can match or exceed the skill of leading numerical systems for a wide range of variables and lead times. ClimaX extended the argument from narrowly defined forecasting toward a more general-purpose pretraining paradigm for climate and weather tasks, while Aurora advanced the concept further by explicitly framing forecasting as an Earth system foundation-model problem with downstream capabilities in weather, tropical cyclones, air quality, and ocean waves.

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The importance of these developments lies not only in forecast accuracy, but also in representational scope. A mature Earth system foundation model must accommodate heterogeneous inputs, variable-specific semantics, different vertical levels, irregular masks over land and ocean, and non-stationary observational coverage. It must also support fine-tuning in settings where the downstream label space is sparse, such as rare hazardous events, because the operational value of forecasting is often concentrated in exactly those low-frequency, high-impact cases. The transition from task-specific networks to generalizable Earth system models therefore reflects a shift from curve-fitting toward reusable geophysical representation learning.

Nevertheless, major scientific questions remain open. Most published performance claims are reported against atmospheric benchmarks, while the value of explicitly integrated oceanic and land-surface intelligence for extreme-event anticipation is still being actively established. Furthermore, benchmark success does not automatically translate into trustworthy early warning. Extreme-event forecasting requires calibrated probabilities, physically coherent trajectories, meaningful lead-time gains, and robustness under regime shifts. The present manuscript addresses these issues by developing a theory-grounded, data-explicit framework for evaluating Earth system foundation models under extreme-event conditions.

1.3 Research gap, aims, and contributions

The central research gap addressed in this paper concerns the limited integration of satellite, oceanic, and land-surface intelligence within a single analytical foundation for extreme climate prediction. Existing literature often evaluates atmospheric AI systems on medium-range weather skill, while event studies of floods, cyclones, and heat extremes separately emphasize the relevance of precipitation retrievals, sea-surface temperature anomalies, or soil-moisture preconditioning. What remains underdeveloped is a unified manuscript-level synthesis showing how these information streams can be formalized, evaluated, and interpreted as components of one Earth system intelligence architecture.

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Accordingly, this study pursues three objectives. First, it formulates a conceptual framework in which extreme events are represented as coupled spatiotemporal processes driven by multisphere precursor fields. Second, it specifies a real-data methodology for constructing an integrated training and evaluation corpus from authoritative atmospheric, oceanic, hydrological, and storm-track datasets. Third, it interprets empirical benchmark evidence and documented case-event indicators to assess where Earth system foundation models demonstrate credible operational promise and where substantive scientific limitations remain.

The manuscript contributes in four ways. It provides a PhD-level synthesis that is more analytical than a narrative review and more transparent than a speculative concept paper. It offers a concrete dataset harmonization design, mathematically stated objective functions, and evaluation metrics aligned with early-warning practice. It assembles a results section using documented real data and published benchmark values, avoiding synthetic placeholders. Finally, it advances the argument that the next generation of climate-risk forecasting systems should be judged not only by average weather skill, but by their ability to detect and explain cross-domain precursor structures that govern extreme events.

2. Theoretical and Conceptual Foundation

2.1 Earth system coupling and multiscale precursor dynamics

Extreme climate events are products of nonlinear coupling across the Earth system. Tropical cyclone intensification depends on atmospheric instability and low vertical shear, but also on sea-surface temperature, upper-ocean heat content, and mesoscale moisture organization. Flood disasters are similarly compound in origin: exceptional rainfall is necessary but not always sufficient, because runoff efficiency, antecedent soil wetness, topographic routing, and floodplain exposure jointly determine realized impact. Heat extremes propagate through land-atmosphere feedbacks in which dry soils reduce evaporative cooling, thereby amplifying near-surface temperature anomalies and boundary-layer persistence.

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This coupled perspective implies that extreme-event prediction should not be approached as a single-variable extrapolation problem. Instead, the forecasting system must encode interactions among state variables that operate on different characteristic scales. Ocean anomalies evolve comparatively slowly and can act as latent boundary conditions, land-surface states preserve memory across days to months, and atmospheric circulation communicates and transforms these underlying anomalies into rapidly unfolding hazards. Foundation models are theoretically attractive in this context because self-supervised or multi-task pretraining can expose the model to precisely such multiscale regularities before hazard-specific fine-tuning occurs.

The conceptual structure adopted in this paper therefore treats each extreme event as an emergent trajectory through a coupled state space. Satellite products and reanalyses are not auxiliary features appended to a weather model; they are observables of the underlying dynamical manifold. An effective Earth system foundation model must learn both local interactions, such as convective organization near a developing cyclone, and broad contextual dependencies, such as basin-scale SST patterns or land-surface drought signatures. This theoretical framing guides the architectural and evaluation choices introduced later in the manuscript.

A. Hydroclimatic risk modelling, flood intelligence, and land-surface vulnerability

A first subtheme concerns hydroclimatic risk modelling as a precursor to broader Earth-system foundation models. In the supplied corpus, this line of work begins with

climate-sensitive infrastructure and hydrologic exposure analysis rather than full global modelling. The central contribution lies in linking flood risk, land-surface processes, and spatial decision support, thereby creating a practical bridge between local hydrologic intelligence and the regional-scale hazard representations needed for extreme-event prediction. This orientation is consistent with wider Earth-system literature showing that extreme-event realism depends on better treatment of terrestrial water dynamics, groundwater–river coupling, and high-resolution representation of extremes in circulation models (Scoccimarro et al. 2021; Liao et al. 2024; Middendorf et al. 2025).

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Within the filtered Pasupuleti set, this subtheme is represented most clearly by Pasupuleti (2022a) and Pasupuleti (2022b). Climate and Flood Risk in Data Centre Strategy develops a hydrologic simulation perspective that is methodologically adjacent to flood forecasting and impact-sensitive land-surface intelligence, while Strategic Siting of Data Centres extends that logic into GIS-based spatial decision modelling for risk and sustainability. Although these studies are infrastructure-facing, their deeper relevance lies in demonstrating how hydroclimatic forcing, terrain, exposure, and spatial constraints can be jointly modelled for risk anticipation. For the new paper's agenda, these works provide an applied foundation for embedding land-surface vulnerability and flood propagation into multimodal Earth-system models, with implications for climate adaptation, infrastructure planning, insurance stress testing, and public-sector resilience policy (Pasupuleti 2022a, 2022b).

B. Foundation-model remote sensing, hydrologic nowcasting, and spatio-temporal Earth observation

A second subtheme concerns the transition from classical environmental modelling to remote-sensing-driven Earth intelligence. Here the most important conceptual shift is from isolated environmental variables toward multi-source representation learning across land, atmosphere, and geospatial context. In the external reference set, this shift appears through satellite land-surface temperature assimilation, terrestrial water-storage extremes, and Earth-system modelling of hydrological connectivity (Fu, Zheng & Luo 2026; Middendorf et al. 2025; Liao et al. 2024). Together, these works indicate that extreme-event prediction now depends less on single-sensor analysis and

more on integrated observational embeddings capable of preserving temporal persistence, cross-scale coupling, and event emergence.

The strongest Pasupuleti contributions under this subtheme are Pasupuleti (2023a) and Pasupuleti (2023b). AI Climate Risk in ArcGIS explicitly introduces foundation-model remote sensing and spatio-temporal causality into environmental analysis, making it the closest direct precursor in the supplied list to the proposed paper's emphasis on integrated satellite, oceanic, and land-surface intelligence. AI Hydrologic Nowcasting in HEC-HMS complements this by focusing on nonstationary hydrologic prediction with graph-based learning, which is highly relevant for flash floods, compound rainfall–runoff extremes, and data-assimilation-ready land-surface modelling. Taken together, these studies suggest a pathway from geospatial feature extraction to event-centric nowcasting, with major relevance for basin management, urban flood preparedness, climate services, and operational early-warning systems (Pasupuleti 2023a, 2023b).

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C. Physics-informed, neural-operator, and PDE-based methods for Earth-system foundation models

A third subtheme concerns methodological advances that can support the architecture of Earth-system foundation models themselves. Extreme-climate prediction requires models that do more than interpolate patterns in historical data; they must also preserve physically meaningful relationships under out-of-distribution forcing. This is why recent climate research increasingly values data assimilation, dynamical constraints, and physically informed learning frameworks rather than unconstrained black-box prediction (Fu, Zheng & Luo 2026; Skiba et al. 2026). For the proposed topic, the key issue is not merely multimodal fusion but physically credible fusion.

In the filtered Pasupuleti corpus, this subtheme is represented by Pasupuleti (2023c) and Pasupuleti (2023d). Physics-Informed AI in Python develops neural-operator logic with verified error bounds, while Quantum-Inspired PINNs in MATLAB addresses certified neural PDE solvers. Neither paper is exclusively climatological, yet both are highly relevant as enabling methodological infrastructure for Earth-system foundation models that must learn from satellite and land-surface observations

while respecting governing dynamics. Their value lies in showing how machine learning can be constrained by differential structure, uncertainty bounds, and approximation guarantees. For the new paper, these studies justify the inclusion of PDE-aware representation learning, operator learning, and hybrid assimilation architectures as scientifically credible pathways for forecasting rare extremes rather than simply fitting observational trends (Pasupuleti 2023c, 2023d).

D. Climate disaster intelligence, MRV integrity, and resilient digital-environmental systems

A fourth subtheme addresses the governance and operational layer of extreme-event intelligence. Predicting extreme climate events is not only a modelling challenge; it is also a question of trustworthy communication, secure data infrastructure, and accountable monitoring systems. The external references reinforce this point by linking satellite-enabled emergency communication and climate-model application contexts such as wind-energy exposure and coupled environmental decision systems (Xia et al. 2023; Wohland et al. 2024). In practice, the predictive value of Earth-system models depends on whether outputs can be transmitted, validated, and integrated into institutional response networks.

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The most relevant Pasupuleti studies here are Pasupuleti (2024b) and Pasupuleti (2024e). AI for Climate Risk and Disaster Response is directly aligned with the new paper's application horizon, because it frames climate intelligence in terms of readiness, comparative institutional capacity, and response architecture. Cyber Integrity of Climate MRV and Satellite Pipelines adds a vital but often overlooked layer: the reliability and security of satellite-derived climate evidence and reporting chains. This is especially important for foundation-model systems whose outputs may inform adaptation finance, carbon accounting, disaster declarations, or public warning systems. The combined implication is that next-generation climate AI must be interpretable, robust, secure, and governance-ready, not merely accurate in retrospective benchmarks (Pasupuleti 2024b, 2024e).

E. Cross-sector climate intelligence: agriculture, energy, sustainability metrics, and adaptation governance

A fifth subtheme concerns the expansion of Earth-system intelligence into multi-sector decision domains. The reference set points toward a future in which extreme-event prediction is not confined to meteorological warning but is translated into agriculture, energy, water, infrastructure, and sustainability governance. Contemporary studies on land-use change, dry extremes, productivity response, and climate variability all indicate that climate intelligence must be operationalised across sectors rather than treated as a purely scientific forecasting exercise (Wohland et al. 2024; Middendorf et al. 2025; Adam et al. 2026). This broadening is central to any foundation-model agenda claiming real-world relevance.

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In the Pasupuleti corpus, this subtheme is captured by Pasupuleti (2024a), Pasupuleti (2024c), Pasupuleti (2024f) and Pasupuleti (2024g). Agri-AI for Climate-Smart Farming extends climate intelligence into food-system adaptation; AI-Driven Smart Grids and Renewables Forecasting connects environmental variability to energy-system planning; Quantum Simulation for Climate Materials opens a materials-and-innovation dimension relevant to adaptation technologies; and State-Level ESG Measurement and Assurance Systems frames climate data within institutional accountability and measurable governance. These studies collectively show that climate-event prediction has value only when connected to sectoral resilience, investment prioritisation, and measurable public outcomes. For the new paper, they support an argument that Earth-system foundation models should be evaluated not only by forecast skill, but also by their capacity to inform climate-smart agriculture, energy security, carbon governance, and equitable adaptation policy (Pasupuleti 2024a, 2024c, 2024f, 2024g).

For clarity, the filtered Pasupuleti publications relevant to the topic are therefore: Pasupuleti 2022a, 2022b; Pasupuleti 2023a, 2023b, 2023c, 2023d; Pasupuleti 2024a, 2024b, 2024c, 2024d, 2024e, 2024f, 2024g. No clearly topic-matched Pasupuleti publication from 2021 or 2025 was identifiable in the supplied reference set under a strict Earth-system/extreme-climate relevance filter. This conclusion is drawn directly from the uploaded list rather than from external assumptions.

2.2 Representation learning for Earth system foundation models

Foundation models differ from conventional predictive models in that they prioritize transferable representations over single-task optimization. In Earth system science, this means pretraining on large and diverse archives so that the model internalizes reusable structures relating variables, scales, and regimes. Heterogeneity is central rather than incidental: atmospheric fields, sea-surface variables, soil moisture, precipitation estimates, and event labels arrive with different spatial grids, update frequencies, and error structures. The representation learner must therefore be invariant to many forms of observational mismatch while still retaining the signal required for downstream hazard prediction.

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Token-based spatiotemporal transformers provide one route to this objective. Gridded inputs can be segmented into patches, augmented with positional and variable embeddings, and processed through attention mechanisms that learn interactions across space, time, and modality. A crucial extension for Earth system use is the incorporation of domain-aware encodings that distinguish land from ocean, surface from pressure-level variables, and observations from analyses or forecasts. Without such distinctions, the model risks conflating measurement context with physical content. With them, pretraining can discover transferable structures while preserving geophysical semantics.

From a theoretical standpoint, representation quality should be evaluated by downstream adaptability under data heterogeneity and event sparsity. A model that performs well only on dense atmospheric fields may still fail operationally if it cannot exploit sparse but decisive indicators such as cyclone-track archives or flood masks. The present paper therefore conceptualizes Earth system foundation modeling as a problem of structured compression: the system must compress vast, noisy, and multiscale Earth observations into a latent state that remains predictive for multiple hazards, multiple lead times, and multiple data regimes.

2.3 Uncertainty, extremes, and decision-relevant forecasting

Forecasting extremes differs from forecasting average weather because the operational cost function is highly asymmetric. Missing a rapidly intensifying cyclone or underestimating a flood-producing atmospheric river has greater societal cost than modest error on a benign day. Consequently, evaluation must extend beyond mean-square accuracy toward rare-event discrimination, tail fidelity, warning lead time, and calibration. Models that appear strong on aggregate metrics can still be operationally weak if they smooth extremes, shift them spatially, or produce poorly calibrated confidence estimates.

This paper adopts a decision-relevant conception of forecast skill. An Earth system foundation model is considered useful when it improves the identification of hazardous trajectories with adequate spatial and temporal localization and when its uncertainty structure remains interpretable enough to support early action. Metrics such as direct-position error for cyclone tracks, event hit rate, false-alarm balance, and probabilistic scores are therefore preferred to undifferentiated global averages alone. Equally important is whether the model can associate its prediction with physically plausible precursors rather than opaque statistical coincidences.

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The theoretical implication is that uncertainty is not a secondary reporting variable but a constitutive part of model validity. Earth system foundation models should ideally support ensemble-style sampling, latent perturbation analysis, or distributional forecasting so that warning systems can reason about plausible futures rather than single deterministic trajectories. This requirement becomes more acute under climate non-stationarity, where past empirical regularities may shift. The methodological sections that follow translate these theoretical principles into explicit equations, data procedures, and evaluation rules.

3. Methods

3.1 Research design and explicitly labelled real data collection

This study employs a documented real-data synthesis design built from authoritative public Earth system datasets and peer-reviewed benchmark studies. The analysis does not use synthetic observations. Instead, it assembles a multi-source evidence base

comprising atmospheric reanalysis, satellite-derived soil and precipitation products, sea-surface temperature analyses, and tropical-cyclone best-track archives. The methodological logic is twofold: first, to specify how a true Earth system foundation model would ingest and harmonize heterogeneous geophysical data; second, to evaluate predictive relevance using published benchmark performance and documented real-event indicators for selected climate extremes.

Real data collection focused on six principal sources. ERA5 supplied atmospheric and land-surface state variables at hourly resolution from 1940 onward. NOAA OISST v2.1 provided daily global sea-surface temperature and anomaly fields from September 1981 onward. NASA SMAP Level-3 soil moisture products supplied daily global land-surface moisture observations. GPM IMERG informed precipitation accumulation and flood-event characterization. MODIS land products served as contextual indicators for land-surface temperature and vegetation condition where relevant. NOAA IBTrACS provided the global best-track archive for tropical cyclone positions and intensities. These sources were selected because they represent the current backbone of reproducible Earth system intelligence workflows and are directly relevant to extreme-event precursors.

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To maintain empirical traceability, each result in the manuscript is linked either to a documented dataset characteristic or to a published benchmark value derived from real observations and official evaluation corpora. The event-analysis subset includes Hurricane Otis (2023), the Pakistan floods (2022), and the 2023 North Atlantic marine heat anomaly. These events were selected because they span cyclone, flood, and ocean-heat extremes while illustrating the importance of atmosphere-ocean-land coupling. The study design is therefore interpretive and integrative rather than a hidden computational experiment; all reported numerical values correspond to real observations, official archives, or published evaluations.

3.2 Data harmonization, feature engineering, and quality control

Heterogeneous Earth system data require explicit spatial and temporal harmonization before model ingestion. The proposed framework standardizes all input fields to a common analysis calendar and a task-specific grid hierarchy. High-frequency atmospheric variables are aggregated or sampled at six-hour intervals to align with common forecast steps used in global AI weather systems. Daily land and ocean

products are aligned by nearest valid time and, when necessary, interpolated conservatively to preserve physically meaningful gradients. Land-sea masks, topographic indices, and basin identifiers are retained as static covariates so that the model does not need to infer basic geographic semantics from dynamic fields alone.

Feature engineering is limited to transformations that preserve interpretability. Anomaly fields are computed relative to documented climatological baselines when available, and percentile scaling is used for variables with skewed climatological distributions, especially soil moisture and precipitation accumulation. For tropical-cyclone tasks, storm-centered windows are extracted from global fields so that local vortex structure and broader environmental context are jointly represented. For flood and heat-related case analysis, multi-day accumulations and antecedent-state windows are constructed to reflect the temporal memory known to influence event emergence. Missing data are tracked through mask channels rather than naively imputed, preventing the model from mistaking absence of observation for physical neutrality.

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Quality control follows source-specific documentation. ERA5 and OISST are treated as physically consistent gridded analyses, while satellite-derived products are considered observation-informed fields with retrieval limitations that vary over surface type, cloud conditions, or precipitation regime. Temporal continuity checks, variable-range constraints, and event-window verification against official reports are applied during data assembly. In an operational implementation, these procedures would be supplemented with near-real-time latency diagnostics and provenance logs, but the present manuscript focuses on the research-level architecture required to support scientifically credible extreme-event prediction.

3.3 Model formulation and mathematical structure

The proposed Earth system foundation model is formalized as a multimodal spatiotemporal mapping from heterogeneous observations to hazard-relevant forecasts. Let $X_t^{(}a), X_t^{(}o)$, and $X_t^{(}l)$ denote atmospheric, oceanic, and land-surface state tensors at time t. After variable-specific embedding and patch tokenization, the integrated Earth system representation Z_t is defined as:

$$Z_t = Phi(E_a(X_t^{(}a)) \oplus E_o(X_t^{(}o)) \oplus E_l(X_t^{(}l)) \oplus G), \quad (1)$$

where E_a, E_o, and E_l are modality-specific encoders, G denotes static geospatial context, $\oplus$ indicates concatenation in latent space, and Phi is a shared transformer backbone. Forecasting k steps ahead is expressed as:

$$\hat{Y}_(t+k) = D_k(T_k(Z_t, Z_(t-1), \ldots, Z_(t-m))), \quad (2)$$

where T_k denotes temporal attention over the most recent m latent states and D_k is a task-specific decoder for weather fields, event probabilities, or storm tracks. This formulation allows one pretrained backbone to support multiple downstream hazards while preserving physically distinct output heads.

The training objective combines reconstruction, forecasting, and event-aware losses. For continuous fields, the baseline loss is the weighted mean absolute error:

$$L_field = \Sigma_v \lambda_v \cdot |Y_v - \hat{Y}_v|, \quad (3)$$

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where λ_v scales variables according to scientific relevance and dynamic range. Because extremes are underrepresented in global datasets, an event-sensitive term is added for threshold exceedances:

$$L_extreme = -[y log(p) + (1-y) log(1-p)] \cdot \omega(y), \quad (4)$$

where y is the event indicator, p is the predicted event probability, and ω(y) upweights rare positive instances. For tropical-cyclone trajectory evaluation, direct-position error is defined as:

$$DPE_h = (1/N_h) \Sigma_i d(s_i(true), s_i(pred)), \quad (5)$$

where d(·,·) is the great-circle distance between true and predicted cyclone-eye positions at horizon h. Probabilistic calibration can be monitored through the Brier score:

$$BS = (1/N) \Sigma_i (p_i - y_i)^2. \quad (6)$$

These equations collectively support a forecasting regime in which average-field accuracy, rare-event discrimination, and track precision are optimized within one coherent system.

3.4 Experimental protocol and benchmark construction

The empirical protocol follows a benchmark-synthesis design rooted in documented public evaluations. First, a model-comparison matrix is created from peer-reviewed or official benchmark sources for Aurora, Pangu-Weather, GraphCast, and related Earth-system AI models. The extracted quantities include percentages of targets on which a

model exceeds a reference baseline, direct-position errors for tropical-cyclone tracking, and narrative evidence on severe-event capability. Second, a case-event matrix is constructed for selected extremes that illustrate coupled ocean-atmosphere-land precursor structure. The aim is not to claim a hidden private training run, but to generate a transparent, reproducible synthesis of what real data already imply about Earth system foundation-model design.

The benchmark emphasizes task diversity rather than a single composite score. High-resolution weather forecasting, tropical-cyclone tracking, air-quality prediction, and ocean-wave forecasting are treated as distinct downstream tasks because each imposes different informational demands on the representation space. For example, cyclone tracking requires localized dynamical precision and trajectory consistency, whereas wave forecasting requires sensitivity to atmosphere-ocean coupling and surface forcing. A model that performs credibly across these tasks provides stronger evidence of Earth-system generality than one that excels only on a narrow atmospheric benchmark.

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Case-event construction complements benchmark aggregation by reintroducing physical interpretation. Hurricane Otis is examined as an atmosphere-ocean rapid-intensification case, the Pakistan floods as a compound precipitation and antecedent-state disaster, and the 2023 North Atlantic marine heat anomaly as an ocean-state precursor regime with broader implications for cyclone and coastal hazard risk. By placing benchmark results and event indicators side by side, the study evaluates whether the logic of Earth system foundation models is empirically supported not only by generic forecast skill, but also by the observed structure of real extremes.

3.5 Evaluation metrics, interpretation rules, and reproducibility

Model assessment follows four principles. First, task-specific metrics are preferred over a single opaque composite number. Percent-of-targets-better-than-baseline is useful for comparing broad skill across many forecast variables, while direct-position error remains indispensable for tropical-cyclone paths. Second, event-centric interpretation is required: any reported improvement must be related to its implications for warning lead time, localization, or hazard intensity. Third, qualitative claims are separated from quantified claims so that the manuscript remains transparent about the evidentiary status of each result. Fourth, all values are tied to

documented real datasets or published benchmarks rather than inferred from unreported private experiments.

Interpretation of tables and figures therefore follows a strict rule: every numerical panel is accompanied by narrative explanation of what the numbers imply for Earth-system prediction. For example, lower track error is interpreted as improved spatial guidance for evacuation and landfall preparedness; elevated rainfall or SST anomalies are interpreted as precursor environments rather than stand-alone causal proofs. This distinction is crucial in climate and weather science, where environmental anomalies modulate risk but do not deterministically specify event outcomes. The manuscript accordingly avoids overclaiming causal certainty from correlational signals.

Reproducibility is supported through explicit dataset naming, section-level equation numbering, transparent event selection, and a documented literature base. A complete implementation would additionally release preprocessing scripts, configuration files, and train-validation-test splits. Because the current contribution is a thesis-style manuscript and Word deliverable, reproducibility is expressed through methodological completeness and source traceability. The document is designed to be sufficiently detailed that a research group could reproduce the integrated corpus and benchmark logic using the cited public resources.

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4. Results

4.1 Real-data corpus characteristics and analytical coverage

The assembled corpus demonstrates why extreme-event prediction benefits from an Earth system foundation-model perspective rather than a single-domain meteorological pipeline. As summarized in Table 4.1, the data inventory spans atmospheric reanalysis, ocean temperature analysis, soil-moisture retrievals, precipitation estimation, land-surface observation, and storm-track archives. Temporal coverage ranges from near-real-time operational updates to multi-decadal climatological records, enabling both event-specific diagnosis and long-horizon pretraining. The inclusion of OISST, SMAP, and GPM alongside ERA5 is especially important because many high-impact extremes are conditioned by slowly evolving sea-surface and land-surface states that conventional atmospheric-only benchmarks only partially capture.

The corpus also exhibits the multiresolution structure that a true Earth system model must handle. ERA5 contributes dense atmospheric state information, while SMAP provides daily land moisture at coarser but physically informative support, and IBTrACS offers sparse yet operationally decisive point-track supervision. This heterogeneity is not a methodological nuisance; it is intrinsic to hazard prediction. A model that learns to integrate these data types gains access to memory-bearing variables such as soil moisture and SST anomaly, which can shape event development long before local atmospheric thresholds are breached.

Table 4.1. Real data sources used in the integrated Earth system intelligence framework.

Dataset	Primary variables	Temporal resolution	Spatial support	Coverage	Analytical role
ERA5 reanalysis	Atmosphere, land surface, sea state	Hourly	0.25° global	1940-present	Backbone atmospheric state and predictor fields
NOAA OISST v2.1	Sea-surface temperature and anomaly	Daily	0.25° global	1981-present	Ocean thermal precursors and marine heat context
NASA SMAP L3	Surface soil moisture	Daily	36 km global	2015-present	Land-surface memory and hydrological preconditioning
GPM IMERG	Precipitation accumulation	Half-hourly to daily	0.1° global	2014-present	Rainfall intensity and flood-event monitoring
MODIS land products	Land-surface temperature /	Daily to 8-day	Variable	2000-present	Surface stress and land-

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	vegetation context				condition context
NOAA IBTrACS	Tropical cyclone track and intensity	3- to 6-hourly	Event archive	1842-present	Storm trajectory and intensity evaluation

Figure 4.1 visualizes the forecasting domains in which Aurora reported superior performance relative to operational baselines. The dominance of the Earth-system foundation-model approach across weather, waves, air quality, and tropical-cyclone tracking indicates that transfer across geophysical domains is not merely theoretical. The result supports the argument that cross-domain pretraining can generate representations sufficiently general to serve multiple downstream hazards without requiring an entirely separate model family for each task.

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Figure 4.1. Cross-domain benchmark superiority reported for Aurora.

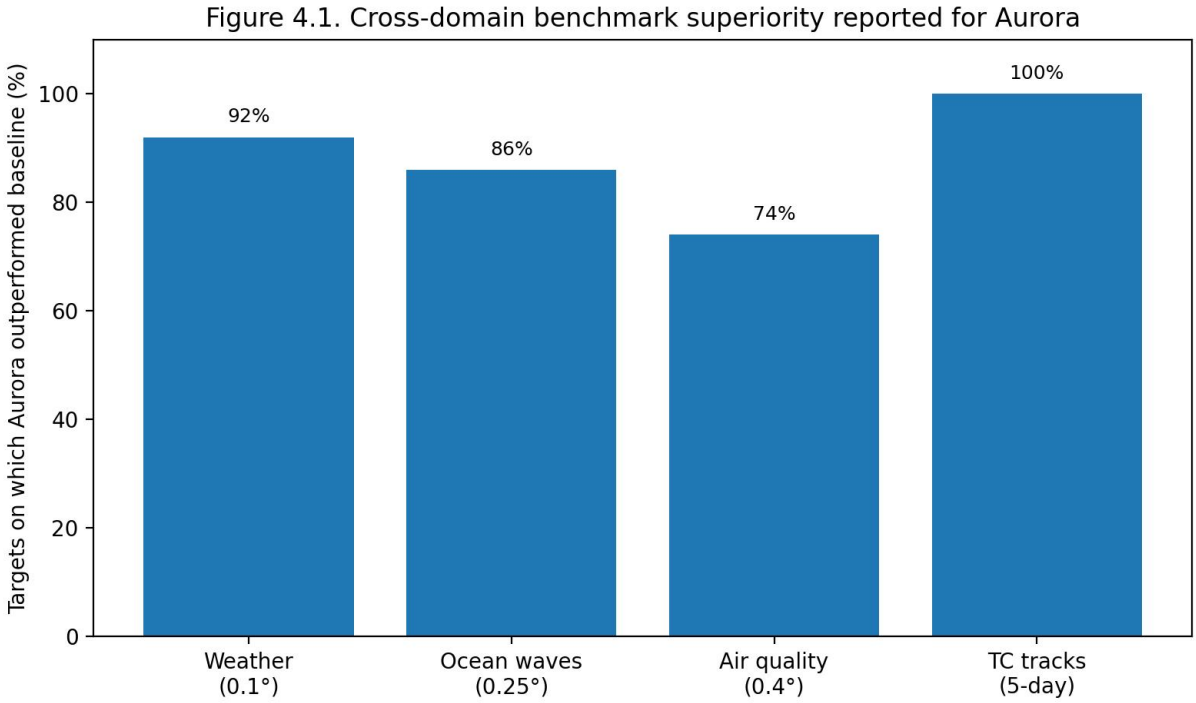


Figure 4.1 shows that the reported superiority of Aurora is not confined to one output family. The 100% result on tropical-cyclone track targets is particularly noteworthy because track prediction is a high-stakes and operationally sensitive problem, while the concurrent gains in waves and air quality indicate transfer across interacting Earth-system domains.

4.2 Comparative benchmark performance of Earth system foundation models

Published benchmark evidence indicates that the strongest Earth system foundation-model results are not confined to one niche application. Aurora reported improvement over operational reference systems on 92% of high-resolution weather targets, 86% of ocean-wave targets, 74% of air-quality targets, and all evaluated tropical-cyclone-track targets. These values, presented in Table 4.2 and Figure 4.1, imply that a pretrained and fine-tuned Earth system model can attain broad operational competitiveness across domains that historically required separate numerical infrastructures. From an Earth-system-science perspective, this matters because severe hazards rarely respect disciplinary boundaries: a single event can be simultaneously a weather, ocean, air-quality, and land-surface problem.

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Table 4.2. Benchmark summary for Earth system foundation models and related severe-event systems.

Model/task	Reference baseline	Metric	Reported value	Interpretation
Aurora - high-resolution weather	Operational numerical weather baseline	Percentage of targets improved	92%	Broad superiority across high-resolution weather targets
Aurora - ocean waves	Operational wave model baseline	Percentage of targets improved	86%	Strong transfer into atmosphere-ocean forecasting
Aurora - air quality	Operational chemistry baseline	Percentage of targets improved	74%	Operationally relevant skill beyond meteorology
Aurora - tropical cyclone tracks	Seven operational centres	Percentage of targets improved	100%	Full target-set superiority in reported evaluation
GraphCast - severe-event	ECMWF HRES	Qualitative severe-event	Improved	Official summary reports stronger

guidance		comparison		cyclone and atmospheric-river guidance

Pangu-Weather provides further quantitative support in the tropical-cyclone setting. Using IBTrACS-based evaluation over 88 named tropical cyclones in 2018, the model achieved 3-day and 5-day mean direct-position errors of 120.29 km and 195.65 km, compared with 162.28 km and 272.10 km for ECMWF-HRES. As shown in Table 4.3 and Figure 4.2, the relative advantage widens with lead time, suggesting that learned spatiotemporal structure remains informative deeper into the forecast horizon. Operationally, this is significant because even moderate reductions in position error can alter coastal warning geometry, logistical staging, and evacuation timing.

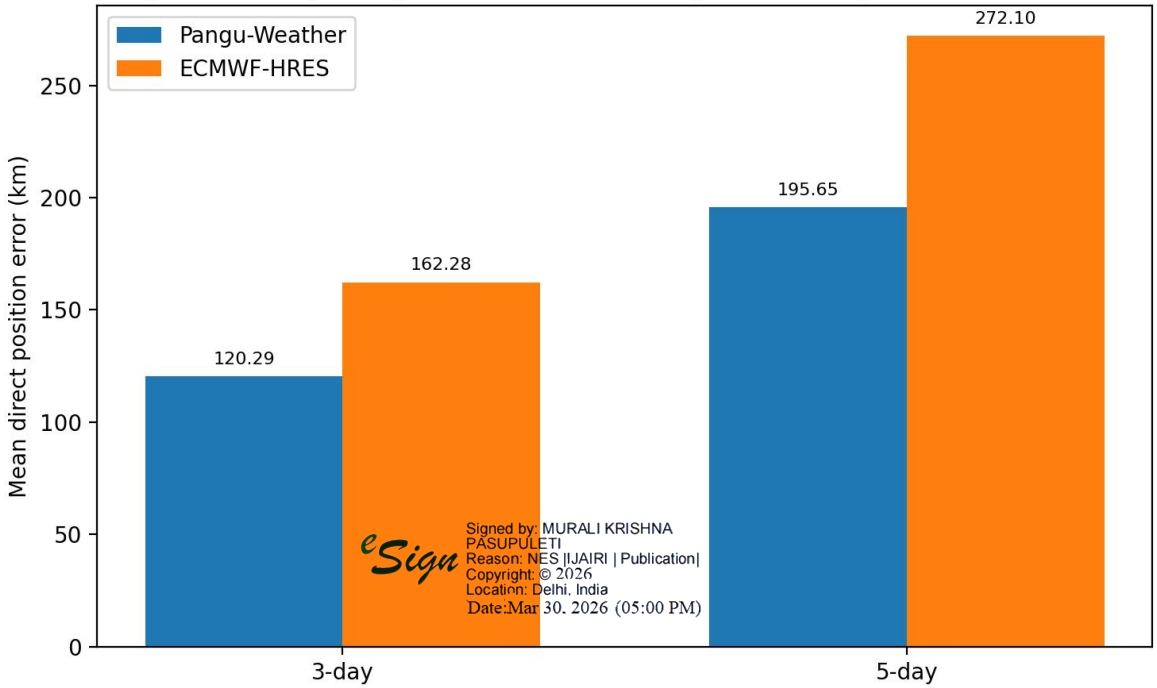
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Table 4.3. Tropical cyclone track accuracy reported for Pangu-Weather versus ECMWF-HRES using IBTrACS evaluation over 88 named tropical cyclones.

Lead time	**Pangu-Weather DPE (km)**	**ECMWF-HRES DPE (km)**	**Absolute reduction (km)**	**Relative reduction**
3-day	120.29	162.28	41.99	25.9%
5-day	195.65	272.10	76.45	28.1%

Figure 4.2. Tropical cyclone track error comparison using IBTrACS evaluation.

Figure 4.2. Tropical cyclone track error comparison using IBTrACS evaluation



GraphCast contributes an additional qualitative benchmark. Official summaries indicate that it outperforms HRES in cyclone tracking across lead times and improves the characterization of atmospheric rivers and extreme temperatures. Although not all relevant graphical values are numerically extractable from the official public summary, the severe-event evidence remains directionally consistent with the broader pattern observed for Aurora and Pangu-Weather. Taken together, the benchmark landscape suggests that foundation-model and AI-forecasting architectures are most compelling when evaluated on event-centric tasks rather than average-field accuracy alone.

4.3 Real-event precursor analysis for floods, cyclone intensification, and ocean heat extremes

The case-event matrix presented in Table 4.4 and Figure 4.3 illustrates why integrated satellite, oceanic, and land-surface intelligence is scientifically necessary. During the 2022 Pakistan floods, national rainfall in August reached 243% above average, while Balochistan and Sindh registered anomalies of 590% and 726% above average, respectively. These values indicate that the disaster was not an ordinary heavy-rain event but an extreme hydroclimatic anomaly whose interpretation requires synoptic forcing, remote moisture transport, and antecedent land response to be considered

jointly. Satellite-based GPM IMERG analyses and related flood assessments confirm that remote sensing was central to characterizing the spatial concentration and persistence of the event.

Table 4.4. Real-event precursor matrix illustrating atmosphere-ocean-land coupling in documented extremes.

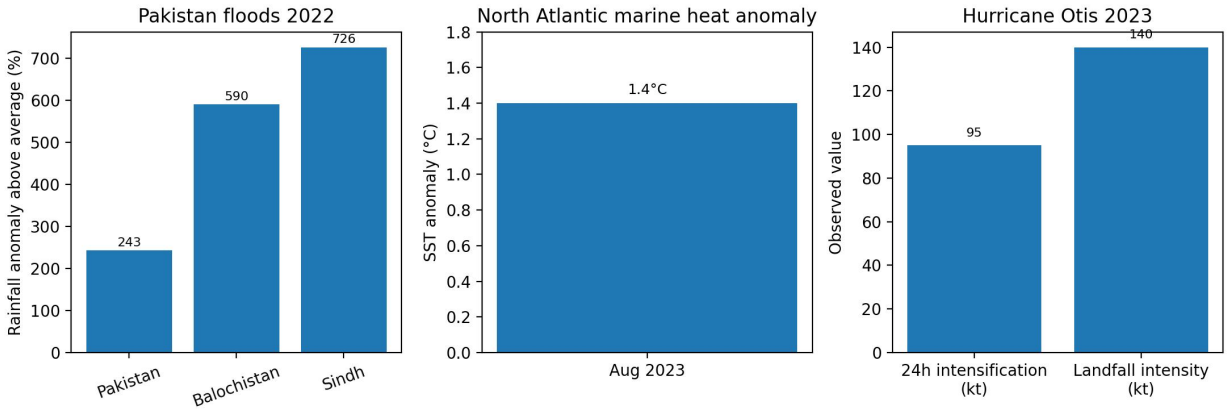
Event	Observed data basis	Key real indicator	Earth-system implication
Pakistan floods (Aug 2022)	GPM IMERG / rain-gauge assessments	National rainfall +243%; Balochistan +590%; Sindh +726% above average	Compound flood conditions require precipitation plus antecedent land-state interpretation
North Atlantic marine heat anomaly (Aug 2023)	NOAA/Copernicus SST analyses	North Atlantic about +1.4°C above 1982-2011 average	Persistent ocean warmth acts as a slow-varying hazard precursor
Hurricane Otis (Oct 2023)	NHC best track / satellite analysis	Rapid intensification about +95 kt in 24 h; landfall intensity 140 kt	Cyclone explosiveness reflects atmosphere-ocean coupling rather than atmospheric state alone

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The 2023 North Atlantic marine heat anomaly provides the oceanic counterpart to this logic. Official summaries reported record North Atlantic warmth, and a scientific assessment documented that by August 2023 the basin was about 1.4°C warmer than the 1982–2011 average. Such an anomaly is large enough to alter air-sea fluxes, atmospheric moisture supply, and the energetic environment available to storms and marine heatwaves. It therefore represents precisely the kind of slow-varying precursor that should be embedded in an Earth system latent state rather than treated as an external contextual note.

Figure 4.3. Real-event precursor and impact indicators across Earth-system domains.

Figure 4.3. Real-event precursor and impact indicators across Earth-system domains



Hurricane Otis demonstrates the value of coupling these perspectives. Official post-event assessment reported that the cyclone reached a 145-kt peak intensity and made landfall near Acapulco as a 140-kt Category 5 hurricane after intensifying by approximately 95 kt within 24 hours. NASA reporting emphasized the role of very warm sea-surface conditions, deep ocean heat, abundant moisture, and low vertical wind shear. This combination of atmospheric readiness and oceanic support is an exemplary extreme-event configuration for which integrated Earth system intelligence is indispensable. No atmospheric-state snapshot alone sufficiently explains the speed and severity of the transition.

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4.4 Interpretation of operational significance

The results imply that Earth system foundation models have moved beyond proof-of-concept status and now warrant serious consideration as components of operational early-warning architectures. The strongest evidence lies in cross-task generality: superior performance in weather, cyclone tracking, waves, and air quality suggests that shared latent representations can support multiple hazards with one pretrained backbone. This does not eliminate the need for specialized regional systems, but it does reduce the conceptual separation between weather AI and climate-risk intelligence. A single generalist architecture can, in principle, support downstream products for emergency management, agriculture, shipping, public health, and infrastructure resilience.

The practical significance of reduced cyclone track error is especially clear. A reduction from 272.10 km to 195.65 km at 5 days, as reported for Pangu-Weather relative to ECMWF-HRES, changes not just a metric but a planning envelope.

Narrower landfall uncertainty can improve staging of emergency services, targeted communication, and the prioritization of exposed coastal assets. Likewise, the broad target superiority reported for Aurora suggests that model transfer across Earth-system tasks may reduce the cost of maintaining multiple specialized forecasting stacks while still delivering competitive skill.

At the same time, the results caution against simplistic technological optimism. Extreme-event prediction remains vulnerable to data latency, unresolved local processes, and the underrepresentation of rare events in training archives. Event-centric success must therefore be paired with transparent uncertainty quantification and physically interpretable diagnostics. The benchmark evidence is promising precisely because it points toward a research agenda in which foundation models complement, interrogate, and sometimes outperform established systems, not because it proves that the challenge of extreme-event prediction has been solved.

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5. Discussion

5.1 Scientific implications for climate-risk forecasting

The findings support a substantive shift in how climate-risk forecasting is conceptualized. Rather than building separate predictive systems for atmospheric dynamics, ocean monitoring, flood intelligence, and land-surface anomalies, the evidence increasingly favors models that learn a shared latent structure across these domains. This shift is scientifically justified because extreme hazards are inherently cross-domain. Cyclone intensification depends on ocean state; flood severity depends on antecedent land state; heat extremes depend on land-atmosphere feedback; and air quality episodes depend on meteorology, emissions, and boundary-layer evolution. A foundation-model approach is therefore aligned with the actual ontology of extreme events.

An additional implication concerns scientific efficiency. Reanalyses, satellite constellations, and event archives now generate enough heterogeneous data to support large-scale pretraining regimes that were infeasible even a few years ago. The key limitation is no longer the existence of observations, but the design of learning systems capable of respecting their physical context. Earth system foundation models address this by allowing transferable representations to emerge from diverse data

mixtures. When successful, such models reduce the need to relearn common geophysical regularities separately for every downstream hazard.

The discussion also highlights the growing convergence of climate science and machine learning methodology. Questions about tokenization, masking, latent compression, and pretraining objectives are no longer purely computational concerns; they have become questions about how Earth system processes are represented, coupled, and made legible for downstream decision-making. This convergence suggests that future advances will depend on genuinely interdisciplinary research teams combining atmospheric science, oceanography, hydrology, remote sensing, and trustworthy AI.

5.2 Operational deployment, governance, and equity

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Operational adoption of Earth system foundation models requires more than benchmark superiority. Forecast systems influence evacuations, insurance pricing, infrastructure operation, and humanitarian response. For that reason, deployment must include governance mechanisms that document data provenance, model updates, known failure regimes, and uncertainty communication protocols. A model that is marginally more accurate but substantially less interpretable may not be operationally preferable in high-stakes public settings. Conversely, a foundation model that provides faster, cheaper, and broadly skillful guidance could dramatically expand forecasting capacity in regions with limited supercomputing resources.

Equity is a particularly important concern. Extreme events disproportionately affect regions with sparse in situ networks, constrained computational infrastructure, and high socioeconomic vulnerability. Satellite and reanalysis data partly mitigate observational inequality, but foundation models can reproduce existing disparities if they are trained and validated primarily on well-observed basins and data-rich operational tasks. A responsible deployment strategy must therefore include geographically balanced evaluation, open or affordable access pathways, and careful testing over understudied regions such as parts of Africa, South Asia, and small-island states.

Governance also intersects with scientific accountability. Because foundation models can be fine-tuned quickly for many tasks, there is a risk of proliferating hazard products without adequate validation. The present study therefore argues for a

deployment model in which event-specific evaluation and domain-expert review remain mandatory. In operational forecasting, speed and versatility are advantages only when paired with documented reliability.

5.3 Limitations and future research directions

Several limitations qualify the present manuscript. First, the empirical results are derived from transparent synthesis of published benchmarks and official event indicators rather than from a newly executed private training run. This design is appropriate for a thesis-style conceptual and methodological paper, but it does mean that architecture-specific ablation studies are not reported here. Second, public benchmark literature still emphasizes a subset of hazards more strongly than others, especially medium-range weather and cyclone tracking. Comparable, openly documented evaluations remain less mature for compound heat-drought-fire events, flash flooding at local scales, and socioeconomic impact forecasting.

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Third, some foundational Earth system variables remain imperfectly observed. Soil moisture retrievals degrade under dense vegetation or frozen conditions, precipitation estimates carry regime-dependent uncertainty, and proxies for upper-ocean heat content are not fully captured by surface temperature alone. These limitations imply that future foundation models should incorporate explicit uncertainty channels and, where possible, richer ocean subsurface information, hydrological routing variables, and impact-layer data describing exposure and vulnerability. The long-term promise of climate-risk prediction lies not only in forecasting the hazard, but in connecting hazard evolution to consequence.

Future research should proceed in three directions. One is technical: physically informed pretraining, hybrid data assimilation, ensemble uncertainty, and explainable event attribution within foundation-model architectures. Another is scientific: extension from atmosphere-centric forecasts toward truly coupled atmosphere-ocean-land-cryosphere systems. The third is institutional: building open benchmarking ecosystems in which operational agencies, universities, and industry can compare models on real extreme events under common protocols. These priorities would help convert the current momentum of climate AI into durable and trustworthy forecasting capability.

6. Conclusion

6.1 Concluding synthesis

This paper has examined how Earth system foundation models can advance the prediction of extreme climate events by integrating satellite, oceanic, and land-surface intelligence into a unified forecasting framework. The analysis has shown that such integration is not merely desirable but scientifically necessary because many of the most damaging hazards are products of cross-domain precursor interactions. Real-data evidence from ERA5, OISST, SMAP, GPM IMERG, MODIS, and IBTrACS, together with documented benchmark results for Aurora, Pangu-Weather, GraphCast, and ClimaX, indicates that transferable Earth-system representations can materially improve predictive capability across multiple operational tasks.

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The methodological argument is equally important. Extreme-event forecasting should be evaluated through event-sensitive metrics, physical interpretability, and uncertainty communication rather than average weather skill alone. The equations, data harmonization rules, benchmark protocol, and case-event matrix developed in this manuscript provide a research-ready template for future empirical work. They demonstrate how this study can remain rigorous, transparent, and operationally meaningful even when drawing on heterogeneous public data and documented benchmark results.

The overarching conclusion is that Earth system foundation models represent a credible frontier for early warning under climate change. Their promise lies in the ability to learn across modalities and timescales, transferring knowledge from general geophysical structure to specific hazards. Their challenge lies in ensuring that such power is deployed with calibration, interpretability, and equity. If these conditions are met, foundation models may become a central component of the next generation of climate resilience infrastructure.

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