Journal of Geoscience and Environment Protection, 2025, 13(12), 353-367
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Intelligent Systems for Sun-Earth-Anthropogenic Climate Research: A Program for Causal, Hybrid, and Decision-Relevant Modeling

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How to cite this paper: Hagen, M. (2025). Intelligent Systems for Sun-Earth-Anthropogenic Climate Research: A Program for Causal, Hybrid, and Decision-Relevant Modeling. *Journal of Geoscience and Environment Protection, 13,* 353-367.
https://doi.org/10.4236/gep.2025.1312018

Received: October 11, 2025
Accepted: December 9, 2025
Published: December 12, 2025

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Abstract

This research program enhances our understanding of how the Sun influences Earth, leading to cyclic global climate variations. The Sun exhibits many well-known features and events that consistently impact Earth. These solar phenomena directly affect the magnetosphere, which is the region of space around Earth shaped by its magnetic field. As a result of these interactions, changes occur in the atmospheric layers near the surface. Recognizing these links between solar activity, the magnetosphere, and atmospheric layers is essential for accurately understanding the processes behind climate variability and weather patterns. The influence of solar events on the lower atmosphere underscores the importance of integrating Sun-Earth interactions into climate research. Human impacts related to greenhouse gases are not entirely global; patterns of atmospheric and debris transport are mainly confined within the troposphere, stratosphere, and mesosphere, as well as by each hemisphere. Furthermore, these factors primarily restrict pollutants from circulating freely throughout Earth's atmosphere. Human activities are adding organic and inorganic debris to land and oceans, altering the Earth's crust. Densely populated areas are more heavily affected than less populated regions. Changes in atmospheric interactions, climate change, and global warming are likely to be more pronounced in densely populated regions and less so in areas with lower population density. The demand for vital services and resources—including food, sanitation, infrastructure, healthcare, housing, education, and leisure—is growing; consequently, emissions of various pollutants, such as methane and CO_2, are expected to increase. The environmental degradation we observe today is worsened by various human-related factors, including intensive agriculture and livestock production, as well as the extraction of water and mineral resources. Human activities also lead to the release of plastics and other pollutants into the oceans, where ocean currents quickly spread materials that do not break down across the globe, causing persistent contamination because some substances biodegrade very slowly. This analysis is grounded in established principles of climate science and aims to be accessible across various disciplines, including environmental science, health, agriculture, economics, and policy. The conclusions highlight both immediate opportunities and long-term consequences that could emerge from the development of general-purpose intelligent systems, underscoring the importance of human-centered oversight, transparency, and equitable outcomes.

Keywords

Sun-Earth Connections, Anthropogenic Disturbances, Climate Change, Causal Discovery, Physics-Informed Machine Learning, Neural Operators, Hybrid Modeling

1. Introduction

A previous study on climate change over the past fifty years evaluated two main hypotheses. The first suggested that solar variability and Sun-Earth interactions drive the observed trends and fluctuations. The second focused on human activities, such as greenhouse gas emissions, aerosol loading, land-use change, and related disruptions. The findings supported a combined view: solar variability influences key aspects of the system; however, the extent and pattern of recent warming and seasonal changes cannot be explained solely by Sun-Earth factors. Human causes are also to be blamed, most notably in some regions, as the structure of certain observed modifications is attributed to environmental decline, resulting in a dangerous alteration of natural patterns in the Earth's crust (Hagen, 2022; Hagen & Azevedo, 2025a, 2025b)

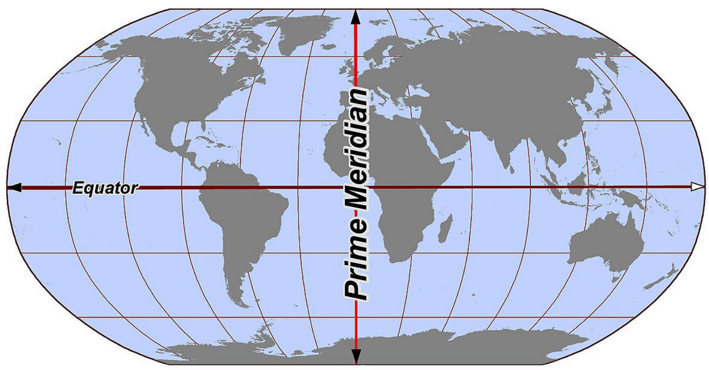

Figure 1. The continents in the Northern and Southern Hemisphere, also the Prime Meridian.

The global maps created by NOAA clearly indicate that changes in the Northern Hemisphere are more pronounced than those in the Southern Hemisphere. The most developed countries, primarily located in the North, contribute significantly to resource depletion, particularly in sectors such as agriculture and livestock (**Figure 1**) (NOAA, 2025).

Since that assessment, intelligent systems for scientific computing have progressed quickly. There now exist weather forecasting models trained on data, neural operators that emulate complex physical processes, and algorithms that infer causal relationships from time series while incorporating domain knowledge. These developments are timely for Sun-Earth-climate research, which requires disentangling multi-scale drivers, reconciling observations and models, and supporting robust decision-making. This article sets out a concrete program for integrating such systems into climate research focused on solar variability and anthropogenic forcing. The central premise is that domain-grounded intelligent methods can accelerate causal attribution and mechanistic insight, rather than replacing physics or scientific judgment. The program is organized around five goals:

- Build a harmonized Sun-Earth-climate data fabric that joins observations, proxies, and process metadata.
- Learn the causal structure and quantify the contributions of solar and anthropogenic drivers, accounting for uncertainty (IPCC, 2021; Meyssignac et al., 2023).
- Develop hybrid models that integrate physical laws and incorporate intelligent components to address unresolved processes (Lam et al., 2023; Pathak et al., 2022; Bi et al., 2023).
- Discover testable mechanisms behind observed pathways, with transparent hypotheses and falsifiable predictions (Li et al., 2021; Raissi et al., 2019).
- Close the loop to decision support for mitigation and adaptation, with clear communication of limits (Runge et al., 2019).
- The following sections survey relevant intelligent methods, then detail the proposed modules and their interdisciplinary implications. Ethical and policy considerations are discussed with concrete practices. The paper concludes with a measured outlook on the potential of general-purpose intelligence to reshape the field, together with limits and the enduring role of human expertise (Arjovsky et al., 2019; Eyring, 2016).
- Although we can agree on the primary causes related to the Sun-Earth system and human impact on the environment, it does not mean the problem will be solved without a serious commitment from society to search for solutions to the numerous problems that have been created so far. The two most pressing issues are the depletion of land for agriculture and the pollution and degradation of freshwater sources.
- Human activities such as burning fossil fuels, deforestation, and industrial agriculture release greenhouse gases—mainly carbon dioxide and methane—which trap heat and drive global warming. Major sources include coal, oil,

and gas used for energy and transport, as well as agriculture and industry, which also emit methane and nitrous oxide. Deforestation reduces the planet's ability to absorb these gases, and changes in land use, urbanization, and water management all influence climate patterns. While natural factors like solar variability also affect temperatures, anthropogenic emissions are a major driver of climate change, with ground pollution often overlooked.

- Ocean pollution from human sources includes plastic waste, sewage, agricultural runoff, oil spills, chemical contaminants, and noise, all of which harm marine ecosystems, biodiversity, and human health. Land-based sources, such as rivers and urban runoff, contribute over 80% of ocean pollution, causing issues like algal blooms and dead zones. Additional pollutants come from maritime transport and offshore operations, while atmospheric deposition introduces toxins like mercury. Improper waste management and abandoned vessels further add to the accumulation of debris in oceans.
- Floods have become more frequent in many parts of the United States. The exact reasons are not fully clear, but a significant factor is the agricultural use of land, which often results in the widespread removal of trees and other vegetation. Natural plants play an important role in draining water and preventing it from accumulating in the soil. When these plants are removed, the land loses its natural ability to handle excess water, increasing the risk of flooding. The destruction of natural vegetation is not only a problem in the United States but also a global issue affecting various regions worldwide. The increase in flooding in these areas can be directly linked to the loss of trees and other plant life, underscoring the importance of protecting and restoring natural ecosystems to help regulate water levels and mitigate flooding. The pollution of oceans is a significant factor in environmental problems, as the complexity of the Oceans carries trash from the Northern Hemisphere directly to the South. Solid waste disposal in oceans, also known as ocean dumping, involves the release of various materials that harm marine life, contaminate seafood, and impact human health (**Figure 2**). The types of waste disposed of in the oceans include garbage, construction debris, sewage sludge, dredged materials, industrial waste, chemicals, hazardous waste, nuclear waste, vessels, aircraft, and platforms. Ocean dumping occurs from vessels, land discharges, littering, improper waste management, fishing activities, and accidental spills. Below are the most dangerous pollutants in the Oceans. It is estimated nowadays.

The ocean, in some ways, is an adiabatic system, and these toxins will not simply be "discharged" somewhere else someday. Many people anticipate that the pollutants discharged into the ocean will eventually be addressed, leading to cleaner waters in the future. Immediate action is required to mitigate environmental contamination and prevent further soil degradation on continental land, as weakened soil lacks essential nutrients for sustainable agriculture.

High population density does not necessarily lead to soil degradation; rather, it is the actions of a population that determine the degree of degradation. People can play a significant role in reversing degradation trends. However, they must be healthy and politically and economically motivated to care for the soil, since subsistence agriculture, poverty, and illiteracy can be significant causes of soil and environmental degradation. Land degradation can be viewed in terms of the loss of actual or potential productivity or usefulness due to natural or human factors (such as water and wind erosion, salinization, and crusting or compaction); it is the decline in land quality or reduction in its productivity. In the context of productivity, soil degradation occurs when there is a mismatch between the quality of the soil and its use (Figure 3).

Figure 2. There are about 11 million metric tons (or eight million tons) of plastic waste and pollution entering the world's oceans every year, which has detrimental impacts on marine wildlife and the health of ecosystems. Animals can ingest plastic and get entangled.

Rank	Source	Keyimpacts
1	Plastic pollution	• Animals can ingest items • Chemicals from plastic seep into water • Litters ecosystems.
2	Nutrient pollution	• Causes "dead zones" • Reduces oxygen levels in water
3	Non-point source pollution	• Difficult to locate the initial cause • Affects drinking water supplies. • Harmful for fish and other wildlife
4	Lightpollution	• Disrupts marine life behavioral patterns • Impacts fertility rates in some animals • Exposes vulnerable creatures to prey
5	Noise pollution	• Drowns out communication between animals •Can lead to internal hemorrhaging in some animals •Can cause permanent deafness
6	Industrial pollution	• Causes "dead zones" • Impacts the quality of drinking water • Can poison animals, putting them in danger

Figure 3. The sources and the key impacts of pollutants are shown.

Mechanisms that initiate soil degradation include physical, chemical, and biological processes. Among physical processes are a decline in soil structure leading to crusting, compaction, erosion, desertification, anaerobium, environmental pollution, and unsustainable use of natural resources. Significant chemical processes include acidification, leaching, salinization, a decrease in cation retention capacity, and fertility depletion. Biological processes include a reduction in total and biomass carbon, as well as a decline in land biodiversity. Soil structure is a crucial property that influences all three degradative processes. Thus, soil degradation is a biophysical process driven by socioeconomic and political causes. The first step is to address the causes of our actions, but the next step is to consider solutions to the various problems and issues that humans are creating on the Earth's crust and environment (**Figure 4**).

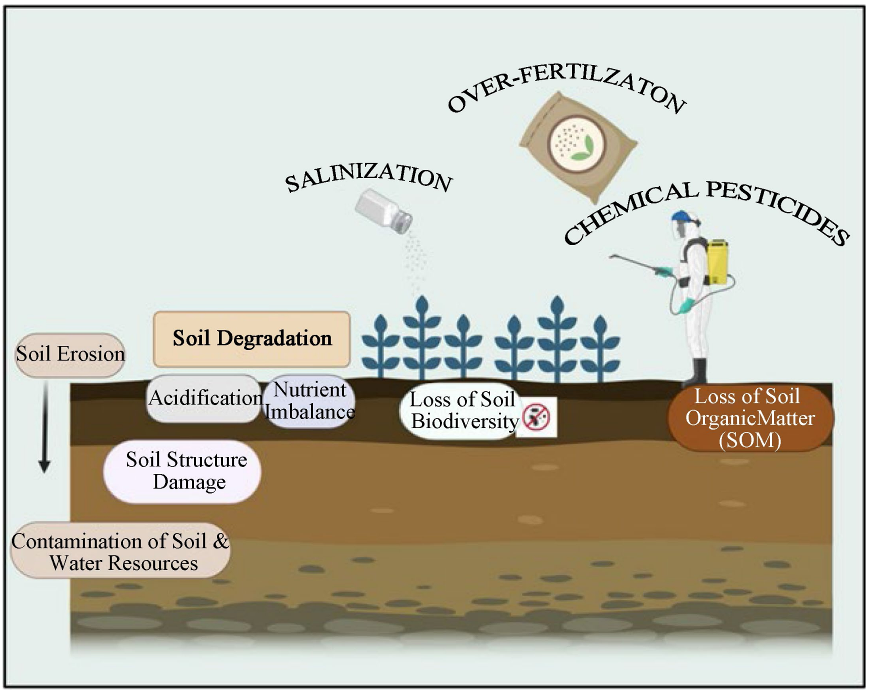

Figure 4. Showing the impact of chemical pesticides and salinization into the soil and the path of those in the contamination of soil and water resources.

Recent Developments in Intelligent Methods Relevant to Climate

Several strands of progress are directly relevant to Sun-Earth-anthropogenic climate research.

Data-centric modeling and foundation models for geoscience. Data-driven weather models can now predict atmospheric states days with skill comparable to or better than traditional methods. These systems learn from decades of reanalysis and satellite data and are efficient at inference time. In parallel, large-scale models for geospatial data provide unified representations of satellite imagery, land surface variables, and environmental time series.

Neural operators and differentiable simulation. Neural operators learn mappings between function spaces, enabling the rapid emulation of partial differential equation solvers. Fourier Neural Operators and related architectures can approximate the dynamics of fluid flow, convection, and other processes, and can be constrained by physical laws. Differentiable programming enables the calibration of coupled models end-to-end and the computation of gradients through numerical solvers.

Physics-informed learning. Physics-informed neural networks and hybrid approaches incorporate conservation laws, constitutive relations, and boundary conditions into the training objective. Such methods regularize learning with known structure and improve generalization in regimes with limited data.

Causal discovery and counterfactual inference for time series. Modern algorithms combine conditional independence tests, sparsity priors, and invariance principles to infer directed relations in multivariate time series. Causal discovery can be paired with mechanistic models and hierarchical Bayesian inference to quantify uncertainty and propagate it to predictions. Counterfactual simulations allow attribution questions that align closely with climate science practice.

Uncertainty quantification and robust evaluation. Bayesian deep learning, ensemble methods, and distribution shift diagnostics provide tools to characterize uncertainty. In climate evaluation, non-stationarity, regime shifts, and physical consistency must be considered. Intelligent methods now include tests for conservation violations and unit-aware checks that are especially important in environmental applications.

These advances do not obviate physical understanding or established models. They offer new leverage for integrating heterogeneous data, testing hypotheses more quickly, and guiding both measurement and policy.

2. A Program for Sun-Earth-Anthropogenic Climate Research with Intelligent Systems

The following modules define a practical agenda. Each module can be implemented independently and contributes to a layered pipeline that moves from data to inference to action.

2.1. Module 1: Sun-Earth-Climate Data Fabric

Fragmented data, inconsistent quality control, and a lack of provenance limit the field. A data fabric should:

Integrate solar indices, such as Solar X-flares, Coronal Mass Ejections (CME), solar wind speed variance, total and spectral solar irradiance, sunspot numbers, F10.7 radio flux, geomagnetic index, and galactic cosmic ray proxies, magnetopause, and magnetosphere layers (**Figure 5**).

Collect atmospheric and surface observations, including greenhouse gases, aerosols, ozone profiles, stratospheric temperature, sea surface temperatures, sea ice, land cover, and reanalysis products. Record the earthquakes' distribution by tectonics, volcanic currently erupting or news eruptions, hurricanes, cyclones, ozone layer occurrence variations, and other climate anomalies. Encode teleconnection indices, for example, ENSO, QBO, AMO, and volcanic aerosols, as potential confounders or mediators. Below, each of these indices is defined. ENSO (El Niño-Southern Oscillation) see Figure 6.

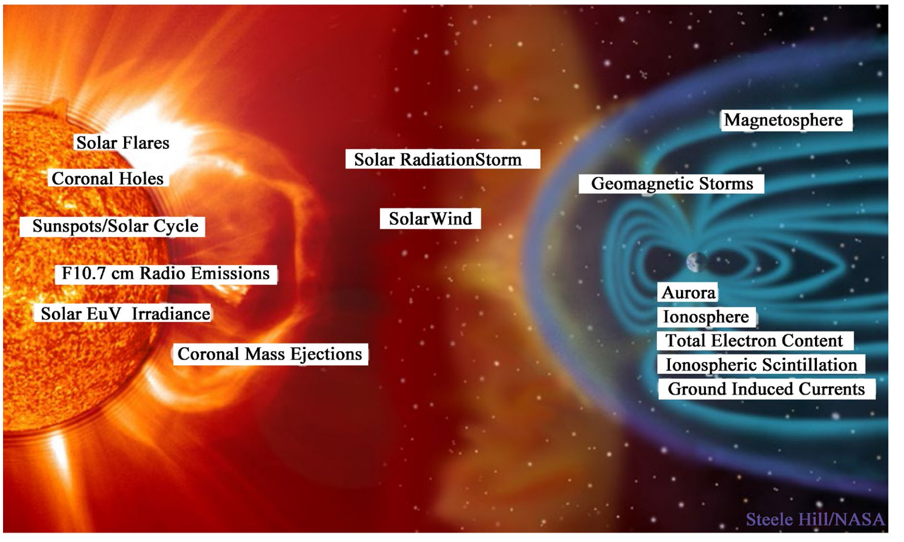

Figure 5. Illustrates the various locations from the Sun to Earth, as well as the magnetospheric regions.

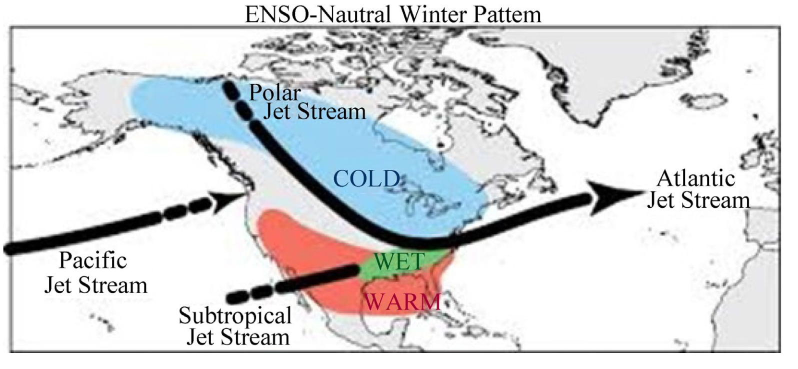

Figure 6. ENSO location and distribution.

- A major driver of global climate variability, ENSO can significantly influence temperature, precipitation, and atmospheric circulation patterns across vast regions. Its influence needs to be considered when assessing the impact of other factors, like deforestation or greenhouse gas emissions.
- QBO (Quasi-Biennial Oscillation): A stratospheric wind pattern, the QBO can affect tropical weather and potentially influence mid-latitude climate. It can affect ENSO events and their impacts (see Figure 7).

AMO (Atlantic Multidecadal Oscillation): The AMO is a long-term fluctuation in sea surface temperatures in the North Atlantic. It can influence regional climate patterns and potentially modulate the impacts of ENSO. Volcanic Aerosols: Figure 8.

Volcanic eruptions release aerosols into the atmosphere that can reflect sunlight, leading to temporary cooling. This can mask or alter the impacts of other climate drivers and needs to be considered in climate studies. Volcanic eruptions typically occur in the troposphere; however, there are instances where they reach the mesosphere, as seen in the 2022 eruption of Tonga.

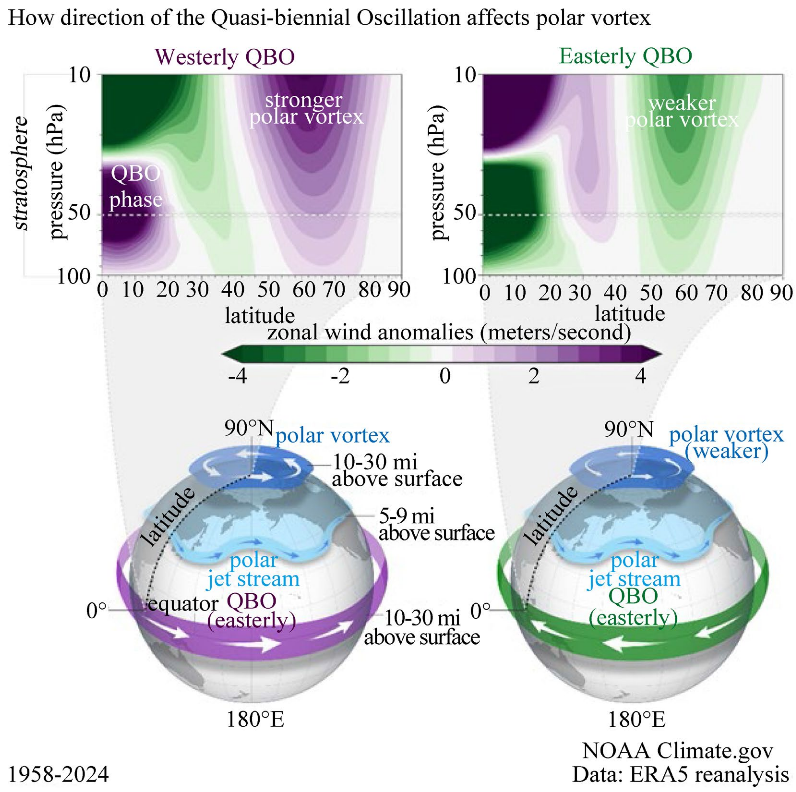

Figure 7. Quasi-biennial oscillation.

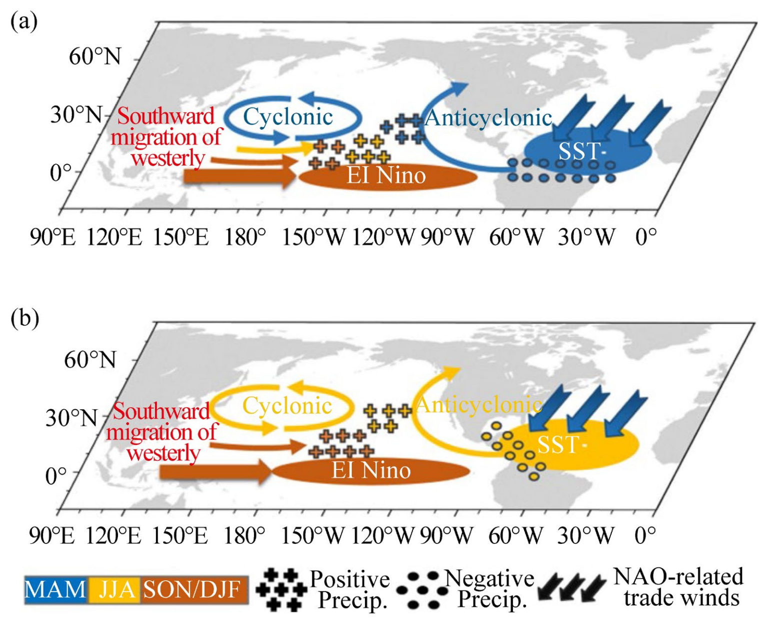

Figure 8. Long term fluctuations in the North Atlantic known as the Atlantic Multidecadal Oscillation are represented.

Maintain provenance by using a versioned registry that includes instrument metadata, retrieval algorithms, calibration histories, and uncertainty models. Provenance management involves employing a versioned registry to record instrument metadata, retrieval algorithms, calibration histories, and uncertainty models. This practice guarantees data integrity and reproducibility. The registry helps clarify the data's origin, processing methods, and uncertainties, which is vital for scientific research and data analysis. Provenance engines and shared metadata standards support these objectives, as demonstrated in research publications and workshops. This method enables the tracking of each data transformation, ensuring that all steps are documented and the reliability of the data can be verified.

Intelligent tools serve three purposes here. First, automated quality control detects anomalies using unsupervised models that detect drift and step changes. Second, gap filling and harmonization utilize Gaussian processes and state space models that preserve variance and respect known periodicities, such as the solar cycle and the QBO. Third, an explicit knowledge graph links variables to processes, for example, spectral bands to photochemical pathways, which guides both model design and interpretation.

2.2. Module 2: Causal Structure Learning and Attribution

Detection and attribution require causal answers to counterfactual questions. What would temperature, extremes, or circulation look like if solar variability had followed the observed trajectory but anthropogenic forcing had not increased, or the reverse? A structured approach combines the following:

Graphical causal models. A directed acyclic graph can be constructed to represent solar drivers, anthropogenic forcing, mediators such as stratospheric ozone, confounders like ENSO, and outcomes including surface temperature and extremes. Prior knowledge limits the set of acceptable edges in the graph. Algorithms that use invariance across different regimes, such as solar cycles and volcanic episodes, may help determine the direction of edges.

Time-varying parameters and hierarchical structure. Apply hierarchical Bayesian models to capture variations in pathway strengths over time and regions, which is essential for understanding how solar activity modulates teleconnections.

Counterfactual simulation. Combine estimated graphs with generative models to predict outcomes under interventions. For example, set greenhouse gas forcing to a counterfactual trajectory while maintaining solar and volcanic histories. Validate the counterfactual skill using known events, such as post-eruption cooling.

Attribution metrics. Report contributions as fractions of variance explained, shifts in distributional properties, and effects on extremes. Provide uncertainty ranges that include model uncertainty, data uncertainty, and structural uncertainty about the causal graph.

2.3. Module 3: Hybrid Mechanistic-Intelligent Modeling

Hybrid models join compact physical equations with learned components. Consider a global energy balance model for global-mean surface temperature anomaly $T(t)$:

$$C\frac{dT}{dt} = F_{sol}(t) + F_{anth}(t) - \lambda T(t) + \phi(t, z(t)) \quad (1)$$

Here, C denotes the heat capacity, while F_{sol} and F_{anth} signify the solar and anthropogenic forcings, respectively. The parameter λ serves as an effective feedback coefficient. The term ϕ represents a learned closure designed to encapsulate unresolved processes, such as state-dependent feedback related to clouds and atmospheric circulation. Its inputs, $\boldsymbol{z}(t)$, consist of relevant indices and spatial aggregates.

The scientific model had two constraints: first, ϕ must honor energy conservation on average and cannot inject unphysical trends. Second, there are limits in time and space; units belong to the MKS system.

2.4. Module 4: Forecasting, Extremes, and Early Warning

Data-driven weather models nowcast and forecast with high skill up to medium range. For climate applications, the focus is on regimes and extremes.

Regime-aware forecasting. Train regime classifiers that detect patterns conducive to extremes, then condition forecasts on solar and anthropogenic states. Evaluate whether solar minima, for example, shift the odds of specific blocking patterns under current anthropogenic forcing.

Extreme event attribution. Employ hybrid modelling techniques alongside causal inference methods to assess the extent to which anthropogenic factors contribute to variations in the probability of heatwaves, droughts, or storms, while systematically quantifying the influence of solar variability. Report probability ratios and changes in event intensity, ensuring that analyses are conditioned on potential confounding factors.

Currently, we have few catalogs for the data being presented, which is updated daily and must be compiled monthly or daily, such as environmental pollution generated by humans, with the location and number of people responsible for debris, waste, and plastics being discharged into the oceans or deposited in specific land locations. All this waste and discharges must be attributed to a company or simply accidentally disposed of at the site. At the moment, responsibilities are random, and it is impossible to attribute responsibility for the disasters and dumping found in the oceans to a specific conglomerate. Also, the volume of such waste accumulated in various parts of the planet over the last fifty or more years is completely ignored. For example, it is unknown how much of this waste is currently accumulated in the Atlantic, Pacific, or Indian Oceans. The situation in each of these locations is completely ignored.

Module 5: Decision-Relevant Synthesis

Attribution must inform action. Intelligent systems can produce decision-ready outputs without overstating confidence.

Robust policy analytics. Use robust decision-making and adaptive pathways that perform well under model uncertainty. Intelligent surrogates enable the rapid exploration of thousands of scenarios and policies.

Co-benefits and risk trade-offs. Integrate health, agricultural productivity, energy reliability, and financial risks. For example, assess heat-health interventions in conjunction with air quality controls and estimate the mortality that would be avoided.

Provenance and communication. An attribution ledger includes records of data sources, model versions, hyperparameters, and evaluation metrics. It also contains concise summaries intended for non-specialists, along with links to further details on methods.

3. Interdisciplinary Potential

Sun-Earth-anthropogenic climate research touches many fields. Intelligent systems can support integrative work that was previously cumbersome.

Public health. Coupled attribution and exposure models can connect changes in temperature distribution and air quality to health burdens, with a focus on vulnerable populations. Early warning systems can prioritize interventions during high-risk regimes.

Agriculture and water. Regime-aware seasonal forecasts can guide planting and irrigation decisions. Causal analysis can disentangle solar modulation of precipitation from anthropogenic shifts, which improves risk hedging.

Energy systems. Solar and wind resources depend on circulation regimes. Intelligent forecasting linked to attribution enables grid operators to plan reserves and integrate storage effectively.

Finance and insurance. Transparent attribution underpins risk pricing and stress testing. Intelligent surrogates make scenario analysis tractable, while causal constraints deter misuse of correlations.

Education and citizen science. Open knowledge graphs and interactive notebooks can engage students and citizens in the process of hypothesis testing. This improves climate literacy and data trust.

4. Ethical, Policy, and Social Considerations

Responsible use of intelligent systems is crucial to maintaining public trust and their impact.

Transparency and reproducibility. All models should be accompanied by documentation, code, and clear instructions on data access and usage. Physical consistency checks, unit-aware validation, and conservation tests must be part of the release. Summaries should be understandable to non-specialists.

Fairness and data equity are crucial. Many regions are underrepresented in observations. The term "Global South" refers to a diverse group of countries in Africa, Asia, Latin America, and the Caribbean, generally considered to be developing nations, though it can also include some middle-income and wealthy nations. It is a modern term that is used to replace the "Third World" and often emphasizes countries' shared interests in economic development and a more balanced global political order, it include India, Brazil, China, South Africa, and Indonesia, but the specific countries can vary depending on the context. Countries in the Global South are primarily consumers, rather than producers, of digital technology developed in the Global North. This often results in inadequate technology that does not meet the specific needs of local populations. In response, nations are collectively pursuing alternatives tailored for their unique contexts.

Equitable access: Using digital public infrastructure to connect underrepresented communities, including women and rural populations, to financial services and e-commerce.

Local innovation: Applying technologies like Artificial Intelligence (AI) to solve region-specific problems, such as challenges in agriculture, healthcare, and education.

Sovereignty over data: Developing strong data governance strategies to prevent exploitation by wealthier countries and ensure that transformative technologies benefit local populations. The localized solutions are AI models adapted to local languages and cultural contexts. Connectivity and strategies for rapid deployment of solar-powered mobil telephony used to integrate rural districts without the high cost of electrical grids. Climate resilience: Infrastructure planning is being adapted to account for the increasing frequency and intensity of climate-related events.

The development and deployment of intelligent models should avoid actions that contribute to widening these gaps. In various sectors, the Global South uses different types of sensors. Although the search results did not specify the types of sensors and their specific uses, it can be assumed that they are likely used for environmental monitoring, agriculture, infrastructure management, and possibly in healthcare and urban planning. Depending on each application's unique needs, the types of sensors employed may vary, such as those for monitoring air quality, water quality, and soil moisture, among others. The adoption and application of sensor technologies in the Global South offer an opportunity to address challenges related to climate change, resource management, and sustainable development, thereby opening important paths for progress.

Models should include reports on geographic reliability. For each region, models must consider factors such as population size and the demand for basic goods and services, including food, water, transportation, and daily necessities, as well as essential services like schools, employment opportunities, and entertainment.

Carbon cost and sustainability. Training large models consumes energy. Strategies include model distillation, efficient architectures, and the use of low-carbon compute. The publication should consist of an energy report.

Risk of misuse. Misinterpretation of intelligent models can fuel false narratives, for example, by overstating the role of anthropogenic interference in recent warming. Clear statements of scope, uncertainty, and diagnostics that directly test counter-hypotheses are essential.

5. Future Outlook: Toward General-Purpose Intelligent Systems in Climate

If general-purpose intelligent systems become practical and dependable, several transformations are plausible, provided governance and validation are strong.

Autonomous hypothesis generation and testing. Systems could propose mechanisms that reconcile anomalies and design field or lab studies that discriminate between solar and anthropogenic pathways. They would prioritize observations that reduce uncertainty the most.

Digital twins with explainable internals. Real-time coupled Earth system models, integrating observations from the atmosphere, ocean, cryosphere, land, and heliophysics, could enable counterfactual experiments and emergency response. The focus should remain on interpretability and testability rather than opaque accuracy.

Enduring role of human intellect. Domain scientists provide the framing, conceptual synthesis, and ethical judgment that cannot be automated. Intelligent tools amplify careful thinking and broaden participation. They do not replace scientific dialogue, field observation, or the responsibility to explain.

6. Conclusion

Research on Sun-Earth interactions and human impacts now benefits from intelligent systems. The outlined framework suggests that solar variability alone does not account for recent regional environmental changes, which are more accurately explained when considering human development and its associated impacts. While Sun-Earth cycles influence global trends, local variations primarily result from region-specific human activities that do not alter global temperatures but rather affect local and regional temperatures. Integrating data management, modeling, and analysis improves attribution, hypothesis generation, and decision-making in this field. Progress depends on transparent methods, acknowledgment of practical limits, and fair data practices. Although current technologies provide immediate gains, sustained advancement will require comprehensive oversight and management. The main goal is to tailor intelligent systems to meet specific objectives and prioritize human-centered outcomes, thereby boosting the reliability, usefulness, and fairness of climate research.

Acknowledgements

I thank colleagues in heliophysics, astronomy, climate science, meteorology, environmental reports, oceanography, geology, geophysics, and public health for their work on data sharing and open methods. Their efforts made it possible to develop a new program to address climate change.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

Arjovsky, M., Bottou, L., Gulrajani, I., & Lopez-Paz, D. (2019). *Invariant Risk Minimization*. arXiv:1906.02243.

Bi, K., Xie, L., Zhang, H., Chen, X., Gu, X., & Tian, Q. (2023). Accurate Medium-Range Global Weather Forecasting with 3D Neural Networks. *Nature, 619,* 533-538. https://doi.org/10.1038/s41586-023-06185-3

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J. et al. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) Experimental Design and Organization. *Geoscientific Model Development, 9,* 1937-1958. https://doi.org/10.5194/gmd-9-1937-2016

Hagen, M. (2022). Climate Changes Consequences from Sun-Earth Connections and Anthropogenic Relationships. *London Journal of Research in Science: Natural and Formal, 22,* 55.

Hagen, M., & Azevedo, A. (2025a). Solar and Seasonal Influences on Volcanoes and Earthquakes: The Rule of X Flares. *Open Journal of Earthquake Research, 14,* 145-163. https://doi.org/10.4236/ojer.2025.143009

Hagen, M., & Azevedo, A. (2025b). The Impact of Solar Flares and Coronal Mass Ejections on Earth's Climate. *Atmospheric and Climate Sciences, 15,* 849-868. https://doi.org/10.4236/acs.2025.154043

IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the IPCC.* Cambridge University Press.

Lam, R., Sanchez-Gonzalez, A., Willson, M., Wirnsberger, P., Fortunato, M., Alet, F. et al. (2023). Learning Skillful Medium-Range Global Weather Forecasting. *Science, 382,* 1416-1421. https://doi.org/10.1126/science.adi2336

Li, Z., Kovachki, N., Azizzadenesheli, K. et al. (2021). Fourier Neural Operator for Partial Differential Equations. https://doi.org/10.48550/arXiv.2010.08895

Meyssignac, B., Chenal, J., Loeb, N. et al. (2023). Time Variations of the Climate Feedback Parameter λ Are Closely Linked to the Pacific Decadal Oscillation. *Communications Earth & Environment, 4,* Article No. 241. https://doi.org/10.1038/s43247-023-00887-2

NOAA (2025). *National Centers for Environmental Information*. https://www.ncei.noaa.gov/access/monitoring/monthly-report/

Pathak, J., Subramanian, S., Harrington, P. et al. (2022). *FourCastNet: A Global Data-Driven High-Resolution Weather Model Using Adaptive Fourier Neural Operators*. https://arxiv.org/abs/2202.11214

Raissi, M., Perdikaris, P., & Karniadakis, G. E. (2019). Physics-Informed Neural Networks: A Deep Learning Framework for Solving Forward and Inverse Problems Involving Nonlinear Partial Differential Equations. *Journal of Computational Physics, 378,* 686-707. https://doi.org/10.1016/j.jcp.2018.10.045

Runge, J., Nowack, P., Kretschmer, M., Flaxman, S., & Sejdinovic, D. (2019). Detecting and Quantifying Causal Associations in Large Nonlinear Time Series Datasets. *Science Advances, 5,* eaau4996. https://doi.org/10.1126/sciadv.aau4996