Frontier Interdisciplinary Strategy

Research Report on Frontier Interdisciplinary Assessment Project of Climate-Ecological Abrupt Change

Frontier Interdisciplinary Assessment Project

of Climate-Ecological Abrupt Change Research Team

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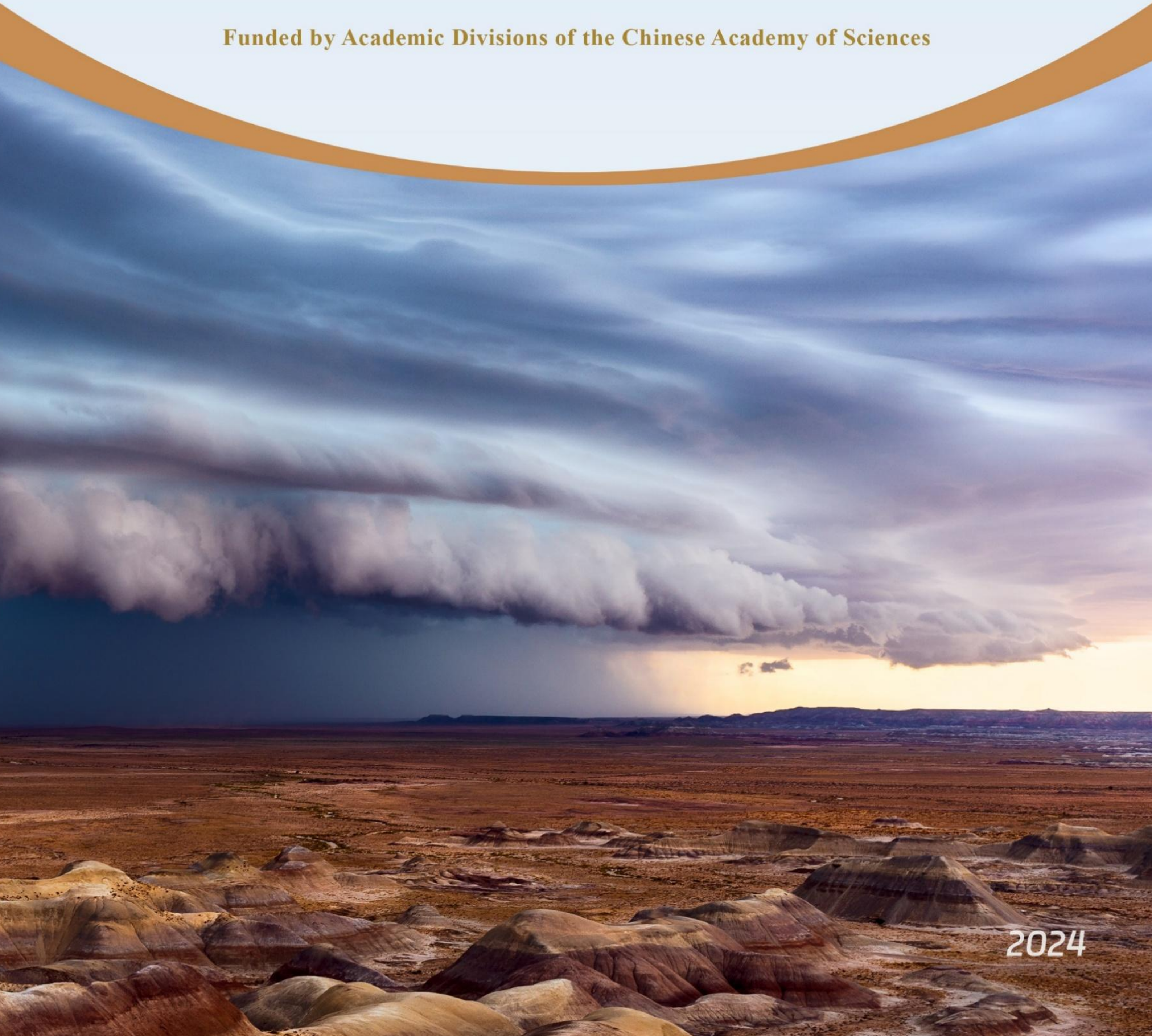

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Abstract

The climate system can undergo sudden, rapid, and drastic changes that exceed human tolerance. Once a tipping point is triggered, it may set off a chain reaction, much like a domino effect, propelling the Earth's climate system toward another tipping point, thereby amplifying the impact of climate change and potentially causing large-scale disasters or even catastrophic devastation across climate, human, and biological systems. Therefore, understanding climate-ecological abrupt changes and implementing adaptive adjustments are crucial to addressing climate change.

At present, the response of ecosystems to climate change and extreme events, as well as their capacity to cope with sudden ecological changes, have become the cutting edge of international academic research, attracting continuous attention and spawning new research opportunities. The theme of “climate-ecological abrupt change” involves a wide range of disciplines, including modern climatology, paleoclimatology, ecology, geology, geography, mathematical and physical sciences, and information science. It is an interdisciplinary frontier field. From a scientific perspective, research on climate-ecological abrupt changes involves interdisciplinary integration, which helps deepen the understanding of global climate change and promotes the study of the evolutionary characteristics of the Earth's complex systems. Strategically, this research can ensure the scientific basis for China's climate change policies and socio-economic decision-making, enhance China's ability to adapt to and combat climate change, and foster the development of predictive and early warning technologies that support socio-economic development.

Research on climate-ecological abrupt changes involves multi-scale, multi-level, and multi-method approaches. Regarding temporal scale, the field of climate and ecological changes spans a broad temporal domain from seasonal, interannual, decadal to centennial and even geological time scales. Spatially, it encompasses different scales ranging from river basins to regions and the globe. The large span of spatial and temporal scales is a prominent feature of this field, with elements at different scales interacting and

responding to each other, which further increases the complexity of research. Research methods at different scales vary and exhibit a trend of cross-integration and increasing complexity.

Based on the principles of scientific rigor fundamental importance, and practical feasibility, the key scientific issues and core technological problems in the field of “climate-ecological abrupt changes” revolve around the logic of “spatial-temporal process of resilience change - tipping point and mechanism of abrupt changes - scientific identification of abrupt changes - early warning and prediction.” These include:

1. What are the patterns of abrupt changes in climate and ecosystems at different spatial and temporal scales, especially the interactions among various elements during these abrupt changes?

2. What are the cascading effects and remote coupling relationships between abrupt changes at different spatial and temporal scales?

3. How can we quantify the changes in system resilience and tipping points to reveal the characteristics and patterns of abrupt changes in the system?

4. How can we effectively integrate short-term monitoring data with paleoenvironmental data, and combine this with multi-disciplinary research methods such as model simulation, to quantitatively determine the tipping points and resilience of climate-ecological abrupt changes at different spatial and temporal scales?

5. How can we thoroughly reveal the driving mechanisms of linear gradual changes and nonlinear abrupt changes in the system, especially clarifying the system’s response mechanisms?

6. What is the process of abrupt changes in the system under the long-term interaction of multiple driving forces?

7. How can we clarify the feedback and mutual feedback relationships among different climate-ecological systems, especially the changes in positive and negative feedback mechanisms during long-term variations?

8. How can we accurately identify the critical elements of the Earth's system and determine their tipping points?

9. How can we identify the key critical elements in China and reveal their mechanisms of abrupt changes? How can we assess the current system's risk of abrupt changes?

10. How can we scientifically predict the risks of future climate and ecological abrupt change events and implement corresponding measures?

11. How can we establish the tipping points and boundary ranges of different ecosystems under the drivers of climate and human activities, as well as the ecological safety space of typical systems?

12. How can we respond to climate-ecological abrupt changes?

13. How can we leverage the positive impacts of abrupt changes and mitigate the negative impacts?

Finally, the report outlines safeguard measures to promote research on climate-ecological abrupt changes in the following two aspects:

First, data observation platforms and technologies: Establish long-term and stable data observation platforms, enhance the deployment of observation systems, develop “space-air-ground-sea” integrated monitoring technologies, and construct a foundational database for climate-ecological abrupt changes.

Second, academic discipline development and talent cultivation: Promote the integration of disciplines such as climatology, ecology, and geology, cultivate strategic and tactical scientists as well as promising young talent, strengthen international cooperation, and initiate global research programs.

Content

Introduction

Since the Industrial Revolution, human activities, particularly the cumulative CO_2 emissions from extensive fossil fuel consumption, have significantly increased the concentration of greenhouse gases in the atmosphere, intensifying global climate change characterized primarily by warming. Rising temperatures, sea-level rise, and the increased frequency of extreme climate events pose severe challenges to human survival and development. These changes also critically impact global natural ecosystems, presenting long-term and substantial threats to food security, water resources, ecology, energy systems, infrastructure, and the safety of lives and property worldwide.

In February 2022, the Intergovernmental Panel on Climate Change (IPCC) released a report warning that over the next two decades, as global average temperatures rise by 1.5°C, the world will face unavoidable multiple climate hazards, some of which will be irreversible. The report underscored the urgent need for stronger and more immediate action to address climate risks. By September 2022, a team led by Professor Timothy Lenton, Director of the Global Systems Institute at the University of Exeter, UK, published a study in Science highlighting that with current global warming of 1.1°C to 1.2°C, the risk of climate tipping points is becoming increasingly apparent. Five critical tipping elements: the Greenland ice sheet, the West Antarctic ice sheet, the low-latitude coral reefs, the Northern Hemisphere permafrost, and Barents Sea ice, are already in the danger zone. The study projected that at 1.5°C of warming, four additional tipping points could be triggered, with five more entering the danger zone. If global temperatures rise beyond 2°C, even more tipping points will be activated [1]. In December 2022, the Organization for Economic Co-operation and Development (OECD) issued a report titled Climate Tipping Points: Insights for Effective Policy Action, calling for a fundamental shift in how climate policies address tipping points.

[1] Armstrong McKay D., Staal A., Abrams J.F., et al. Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*. 2022.377(6611). DOI: 10.1126/science.abn7950.

By March 2023, the IPCC released its Sixth Assessment Report (AR6), focusing on the escalating losses and damages caused by climate change and their future intensification, with the most vulnerable populations and ecosystems bearing the brunt of these impacts.

The climate system can experience sudden, rapid, and drastic changes that exceed human adaptive capacity. Once a tipping point is reached, it may trigger a chain reaction, akin to a domino effect, driving the Earth's climate system toward another tipping point. This can amplify the impacts of climate change and potentially lead to large-scale disasters or even catastrophic destruction of climate, human, and biological systems. Therefore, understanding CEAC and making adaptive adjustments have become the core priorities in addressing climate change.

In sight of this, the CEAC research team organized a series of multidisciplinary discussions across varying scales and domains. Additionally, a questionnaire was distributed to 330 outstanding scientist representatives from China's Project 985 universities, specialized institutions, and research institutes of the Chinese Academy of Sciences (CAS) focused on resources and environment (with 140 responses, including 130 valid submissions). The survey aimed to identify critical tipping elements within China's Earth system. Through these deliberations and surveys, the team identified key scientific issues and technical challenges in the field of CEAC, culminating in the creation of this report. The report advocates for intensified academic research on CEAC, along with enhanced monitoring, interpretation, and prediction of ecological abrupt changes in response to climate change. These efforts aim to strengthen China's ecological resilience and promote the development of a socialist eco-civilization.

1.Scientific Significance and Strategic Value

1.1. Scientific Significance of CEAC Research

Currently, the response of ecosystems to climate change and extreme events, along with their potential to cope with abrupt ecological shifts, has emerged as an international academic frontier, attracting sustained attention and generating new research opportunities. The Past Global Changes (PAGES) program has identified “Thresholds, Tipping Points, and Multiple Equilibria in Earth Systems” as a key interdisciplinary research focus. In 2021, the Royal Society of the UK produced “Climate science, adaptation and resilience” among its 12 critical science and technology areas for achieving carbon neutrality. International frameworks such as the UN Sustainable Development Agenda and the Paris Agreement on climate change have also prioritized resilience as a critical issue. On January 27, 2020, the journal, *Philosophical Transactions of the Royal Society B: Biological Sciences*, dedicated a special issue to “Climate Change and Ecosystems: threats, opportunities and solutions”.

In recent years, China has taken the lead in several international mega-science programs focused on climate, ecology, and environmental research. “The Third Pole Environment” (TPE) program, launched in 2009 under the leadership of Academician Tandong Yao, has created a global platform for scientists studying the Third Pole region and has made a significant international impact. Additionally, the Ministry of Science and Technology of the People’s Republic of China actively promotes the international mega-science program “Environment and Climate Change at the Three Poles”. This initiative aims to (a) establish an integrated air-space-ground-ice-sea observation system for the three poles, (2) uncover the mechanisms behind multisphere environmental and climate change in these regions, and (3) predict future climate and environmental change in the three poles and evaluate their global impacts. The program provides scientific and technological support for climate action, polar security, and the creation of a community with a shared future for humanity. In 2017, the Global Dryland Ecosystem Programme (Global-DEP), co-initiated by Academician Bojie Fu and Dr.

Mark Stafford Smith, attracted active participation from major arid regions worldwide, including the United States, Australia, Mediterranean coastal nations, Africa, and Central Asia. This program produced the Global-DEP Scientific Report, which reveals how dryland social-ecological systems respond to global environmental changes and identifies pathways to enhance ecosystem resilience and achieve sustainable development in arid zones under sustainability goals.

CEAC spans both temporal and spatial dimensions. Temporally, they encompass a broad spectrum from seasonal, interannual, and decadal to centennial or even geological timescales. Spatially, they operate across watersheds, regional systems, and global scales. This vast span of spatiotemporal scales is a defining feature of the field, where elements across different scales interact and respond to one another, significantly amplifying research complexity. To advance understanding of the relationship between abrupt changes and gradual shifts, this report temporarily defines the temporal scope of climate-ecological research as a multi-millennial scale (ten-thousand-year timescale). This framework aims to bridge paleoclimate data and modern modeling approaches, leveraging past climate patterns to anticipate future global change trends. Within the above-defined scope, the scientific significance of CEAC research is underscored by at least the following two aspects:

1. Advancing scientific understanding of global climate change. The study of CEAC integrates multidisciplinary frontiers, including modern climatology, paleoclimatology, ecology, geology, geography, mathematical sciences, and information sciences, representing a critical interdisciplinary domain for academic innovation. By considering the climate and ecological system as a coupled, complex, and continuously adaptive whole, CEAC's research will foster interdisciplinary integration and drive breakthroughs at the intersection of climatology, ecology, and geosciences. Furthermore, this research will improve China's scientific research level and international academic status in the field of global change science.

2. Deeper understanding of the evolutionary characteristics of Earth's complex systems. The study of complex systems reveals that order can emerge from apparent

disorder, while chaos may arise from structured patterns, depending on the scale of observation. Research methods focusing on the characteristics of ecosystem abrupt changes across various scales have become a focal point. At the small scale (e.g., populations, communities), experimental measurements of relevant indicators are typically employed to examine abrupt change behaviors. As the scale increases and systems become more complex, the corresponding research methods tend to adopt more integrated approaches. At the ecosystem scale, methodologies such as large-scale simulation experiments and vulnerability structure analyses are widely applied to uncover regime shifts in ecosystems. At the regional scale, the space-for-time substitution method and remote sensing are commonly employed to monitor ecological abrupt changes. At the global scale, research of ecological abrupt changes primarily relies on model simulations or integrated approaches that combine global field surveys with remote sensing observations. Research in the field of CEAC encompasses diverse spatiotemporal scales, enabling the effective synthesis of multi-scale methodologies. This approach enhances our understanding of emergent phenomena in Earth's complex systems across different scales and hierarchical levels, advancing both paradigm shifts and progress in scientific frameworks.

1.2. Strategic Value of CEAC Research

CEAC represents not only a scientific challenge but also a multidimensional issue that intersects energy, environment, economy, society, and politics. This field has garnered significant attention from governments, academia, and the public worldwide, with its strategic value manifesting in at least three key dimensions:

1. Research on CEAC ensures the scientific basis for China's climate change policies and socio-economic decision-making. In addressing climate change, governments worldwide have implemented multifaceted policies spanning economic, regulatory, and technological domains. International frameworks such as the "Paris Agreement" and the "United Nations Framework Convention on Climate Change" (UNFCCC) underscore the global commitment to addressing climate challenges. On

September 22, 2020, at the 75th United Nations General Assembly, President Jinping Xi announced China's commitment to reaching peak CO_2 emissions by 2030 to attain carbon neutrality by 2060. Different pathways to carbon peaking and neutrality will shape distinct CO_2 concentration trajectories, leading to varied climate and ecosystem impacts. Research on CEAC will assist China in better fulfilling its obligations under the UNFCCC and other related agreements, reducing socio-economic costs associated with mitigating and adapting to future climate change, and providing theoretical guidance and practical strategies for realizing the dual carbon goals.

2. Research on CEAC enhances China's capacity for climate adaptation and actionable responses. The "State of the Global Climate 2022" report released by the World Meteorological Organization (WMO) highlights that extreme climate events, including heatwaves, droughts, and floods, affected millions worldwide in 2022, causing billions of dollars in economic losses. These extreme climate events serve as a stark warning, underscoring both the necessity and urgency of addressing climate change and enhancing risk resilience. We must take tangible actions to reduce greenhouse gas emissions and monitor climate change to mitigate their impacts. An interdependence exists among climate, biodiversity, and human systems. Ecosystems play a positive role in the climate system through their functions in carbon cycling, hydrological processes, and other biogeochemical cycles. When managed sustainably with robust ecosystem and biodiversity science, ecosystems can serve as a cornerstone of human resilience and support societies to adapt to rapid environmental changes. Research on CEAC facilitates the assessment of the effects of future climate change on ecosystems and its associated risks to human survival, providing theoretical and technical support for regulating socio-economic activities and adapting to environmental transformations.

3. Research on CEAE facilitates the development of prediction and early-warning technologies to support socio-economic development. While predicting CEAE remains highly challenging, monitoring key indicators can assess whether climate change and ecosystems are approaching critical thresholds, enabling effective warnings of

significant abrupt shifts. Advancing predictive early-warning technologies and platforms can mitigate the negative impacts of disaster events on China’s agricultural development, ecological restoration, and economic growth, thereby significantly enhancing the nation’s ecological resilience.

2. Theoretical Evolution and Research Characteristics

2.1. Theoretical Connotation of CEAC Research

Abrupt changes refer to rapid, drastic, and irreversible responses of a system to relatively minor external perturbations. CEAC specifically denotes ecological abrupt changes triggered by climate change and feedback mechanisms and responses of ecosystems to climate change.

The origins of Catastrophe Theory can be traced back to the mathematician Henri Poincaré, who identified three key elements in solutions to ordinary differential equations a century ago: structural stability, dynamic stability, and critical sets[2]. Initially, his ideas were not widely accepted by the mathematical community. It was not until 1972 that the French mathematician René Thom (a Fields Medalist), in his work "*Structural Stability and Morphogenesis*", formalized the concept of systems transitioning from one stable state to an unstable state, followed by a sudden shift to another stable state as parameters varied—a process termed "abrupt change" (or "catastrophe"). Catastrophe Theory is closely related to bifurcation phenomena in chaos theory, particularly saddle-node bifurcations, describing irreversible critical transitions between multiple equilibrium states in dynamical systems[3]. Catastrophe Theory employs topology as its methodological tool, builds upon structural stability theory, and utilizes mathematical models to describe processes where gradual changes are interrupted by sudden qualitative shifts. Since its inception, Catastrophe Theory has been applied to address practical problems across multiple disciplines.

According to IPCC reports, abrupt climate change refers to a phenomenon where the climate shifts rapidly (within decades or shorter) and discontinuously from one stable state (or stable ongoing trend) to another stable state (persisting for at least

[2] Yang, M, X., Yao, T. D. Climate abrupt change and the progress of its study (in Chinese). *Discovery of Nature*, 1990(02): 30-34.

[3] Scheffer, M., Bascompte J., Brock W. A., et al. Early-warning signals for critical transitions. *Nature*, 2009,461, 53-59.

decades or as a sustained trend). Such transitions can cause severe disruptions to both human and natural systems [4]. Before the establishment of Catastrophe Theory, climatologists had identified discontinuous and abrupt shifts in climate system states. Research on abrupt changes in climatology originated from analyses of long-term paleoclimate proxy records. Before 1990, paleoclimate studies primarily focused on glacial-interglacial cycles, with a limited understanding of abrupt changes in Earth's climate system. Subsequent ice-core studies from the North Atlantic and Greenland revealed that the climate system could undergo dramatic regime shifts (with temperature fluctuations up to ~10°C) within mere decades. For instance, multiple paleoclimate records, including lake sediment $\delta^{18}O$, pollen, and insect community proxies from Northwestern Europe, demonstrated that the Younger Dryas event (^{14}C dating: 11,000–10,000 BP) exhibited abrupt changes: both its onset (cooling) and termination (warming) rapidly occurred within ~50 years[5], accompanied by a 5–12°C drop in mean annual terrestrial temperatures. In contrast, modern climatology predominantly associates climate abrupt changes with anthropogenic activities, employing climate models to analyze how human-induced alterations to Earth system control parameters (e.g., temperature as a key variable) trigger regional climate regime shifts.

Extensive paleoclimate geological records have consistently documented widespread climate abrupt changes during the last glacial period. The Paleocene-Eocene Thermal Maximum (PETM), occurring ~56 million years ago and triggered by rapid greenhouse gas release, stands out as one of the most pronounced climate abrupt changes. The PETM provides critical insights into contemporary global warming driven by anthropogenic greenhouse gas emissions. While climate warming is the primary driver of ice sheet retreat, paleoclimate studies can provide significant insights

[4] Zhao, Z.C., Luo, Y., Huang, J. b. Global warming and abrupt climate change (in Chinese). *Climate Change Research*, 2021, 17: 114-120.

[5] Atkinson T.C., Briffa K.R.,Coope G R .Seasonal temperatures in Britain during the past 22000 years reconstructed using beetle remains.*Nature*.1987.325:587-592.

into the magnitude of ice sheet retreat under climate warming. The Last Interglacial period (130–116 ka BP) serves as a critical paleo-analogue for contemporary warming, with a global mean temperature anomaly of +0.7°C (+1.3°C in the Northern Hemisphere and +5°C over Greenland) driving substantial cryosphere changes, including ice sheet thinning (~500 m lower than present), potential ice-free conditions in southern Greenland, and a sea-level rise of 2.2–3.4 m above modern levels. These paleo-observations establish a quantitative relationship between climate warming and ice sheet retreat. Additionally, millennial-scale climate simulations reveal distinct hydroclimatic regimes: wet conditions during the Medieval Climate Anomaly, drought dominance during the Little Ice Age, and a return to wet conditions in the modern warm period, collectively demonstrating the high sensitivity of global summer monsoon precipitation to patterns of climate warming.

Ecosystems also undergo abrupt changes. When external disturbances exceed a certain threshold, destabilizing the system's internal equilibrium, abrupt changes occur. In the 1970s, the integration of catastrophe theory and resilience theory provided a framework to explain such ecosystem abrupt transitions. These abrupt changes may emerge from either cumulative gradual pressures or sudden disruptive events. Over time, through the continuous interaction between environmental stressors and biological factors, the biological communities within ecosystems undergo continuous transformations, leading to variations in both their external appearance and internal structures [6]. During this process, when cumulative slow changes in environmental drivers (e.g., grazing intensity) or sudden perturbations (e.g., extreme climate events or natural disasters) reach critical thresholds, the ecosystem undergoes a transformative shift in structure and function, namely an ecological abrupt change [7]. The most salient characteristic of ecosystem abrupt changes is the substantial reorganization of ecosystem structure, including shifts in species composition, horizontal structure, and vertical structure, which further drives changes in ecosystem functioning.

[6] Xu, X. L., Yu, G. R. Theories of ecosystem vulnerability, adaptability and catastrophe based on the mechanisms of ecological succession (in Chinese). *Chinese Journal of Applied Ecology*. 2022, 33(3): 623-628.

The likelihood of CEAC under external forcing is intrinsically linked to system resilience. The concept of resilience originated in physics, denoting an object's capacity to recover after elastic deformation. In 1973, ecologist C.S. Holling adapted this framework for ecosystems, defining it as: "a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist" [7]. Over the past two decades, the definition and conceptual scope of resilience have undergone substantial expansion, evolving from its initial application to ecological systems alone to encompass complex social-ecological systems [8][9], while its analytical framework has progressed from single-scale assessments to cross-spatiotemporal-scale investigations[10][11]. Research on ecological resilience has progressively evolved in its conceptual focus: initially emphasizing the system's maintenance and recovery capacity as measured by return time/rate post-disturbance, then shifting toward persistence and robustness (reflecting resistance to shocks), and ultimately prioritizing adaptive capacities, including adaptation, transformation, learning, and innovation, to ensure sustained development [错误!未定义书签。][12]. In climatology, both academia and policymaking institutions are actively refining the precise definition and conceptual framework of climate system resilience [13]. Current research primarily focuses on the capacity of social-ecological systems to maintain structural and functional integrity under climate change. Beyond analyzing individual

[7] Holling, C.S. Resilience and Stability of Ecological Systems. *Annual Review of Ecology, Evolution, and Systematics*. 1973, 4(1):1-23.

[8] Folke C. Resilience: The emergence of a perspective for social–ecological systems analyses. *Global environmental change*. 2006, 16(3):253-267.

[9] Carpenter S., Walker B., Anderies J. M., et al. From metaphor to measurement: resilience of what to what?. *Ecosystems*. 2001, 4(8):765-781.

[10] Walker B., Salt D.. Resilience Thinking: Sustaining Ecosystems and People in A Changing World. Washington: Island press. 2006.

[11] Gunderson L.H., Holling C.S. Panarchy: Understanding Transformations In Human And Natural Systems. Washington: Island press. 2002.

[12] Zhou X. F., Measuring methods for the resilience of social ecological systems (in Chinese). *Acta Ecologica Sinica*, 2017, 37(12): 4278-4288.

[13] Chen, D, Qin, D., Xiao, C., Su, B., Climate resilience and its implications for China (in Chinese). *Advances in Climate Change Research*. 2019, 15(2): 167-177.

climate subsystems' resilience and stability, studies now emphasize cascading feedback processes during disturbance propagation across subsystems, which may amplify or dampen initial perturbations [14]. That is to say, even when a subsystem exceeds its resilience threshold, the whole system may maintain stability through adaptive adjustments and inter-subsystem linkages. Similarly, the breaching of a critical threshold in one subsystem may amplify the risk of tipping point transgressions in other subsystems.

Complex systems theory indicates that nonlinear systems can exhibit multiple stable states. When control parameters reach critical thresholds, or when external stochastic perturbations are sufficiently strong even below these thresholds, the system can undergo an irreversible transition from one stable state to another, termed a regime shift. This is typically characterized by the duration of stable states before and after the shift vastly exceeding the transition period itself [15]. External forcings on the climate system, such as greenhouse gas emissions, volcanic activity, and solar variability, alter Earth's radiative balance. When key control parameters (notably temperature) exceed critical thresholds, these forcings can trigger internal feedback mechanisms of the climate system (e.g., ice-albedo and water vapor feedbacks), which further result in an abrupt shift to a new stable state. Ecological abrupt changes occur when environmental pressures exceed the system's self-regulatory capacity to respond and adapt to stressors or disturbances. These abrupt changes can manifest in ecosystem structure, processes, and functions. Diverse ecosystem types can undergo regime shifts under specific conditions. Despite their inherent differences, these ecosystems often follow similar transition trajectories when undergoing abrupt changes. Under gradual changes in external environmental drivers (e.g., precipitation, nutrient conditions), ecosystem state variables (e.g., vegetation cover, biomass) initially exhibit stability with minimal

[14] Fang, X., Mechanism of impact of historical climate change to human development in the perspective of social-ecological resilience (in Chinese). *Quaternary Sciences*, 2021, 41(2): 577-588.

[15] Xu, C., Wang, H., Liu, Q., Wang, B., Alternative stable states and tipping points of ecosystems (in Chinese). *Biodiversity Science*. 2020,28(11): 1417- 1430

fluctuations. However, upon crossing a critical threshold, these variables undergo rapid, large-magnitude shifts (e.g., precipitous biomass decline), marking an abrupt change. Furthermore, the system then stabilizes in a new state that typically is irreversible to its pre-shift state.

A core concept in CEAC is the tipping point (also referred to as the critical threshold or abrupt changing point). The tipping point serves as a critical metric for climate change, defined as the threshold beyond which a system undergoes irreversible abrupt changes that persist even after the driving force ceases, with the rate of change becoming independent of the original forcing [4]. Beyond this tipping point, the climate system shifts from one stable state to another. In 2001, IPCC formally introduced the concept of "climate tipping points", identifying nine critical global tipping elements in its reports: (1) dieback of the Amazon rainforest, (2) collapse of Arctic sea ice, (3) weakening of the Atlantic Meridional Overturning Circulation (AMOC), (4) increased wildfires and pest outbreaks in North American boreal forests, (5) global coral reef die-offs, (6) accelerated ice loss from the Greenland Ice Sheet, (7) thawing of boreal permafrost, (8) accelerated ice loss from the West Antarctic Ice Sheet, and (9) collapse of the East Antarctic Ice Sheet.

In 2008, Professor Lenton's team identified 15 critical tipping elements (later expanded to 17) in Earth's climate system in their publication in *PNAS*, encompassing the most vulnerable components of the cryosphere, biosphere, and ocean-atmospheric circulation [16]. These tipping elements exhibit distinct characteristics in their control parameters, critical temperature thresholds, transition rates, and cascading impacts. Consequently, evaluating the trajectory and destiny of Earth's future requires not only a deeper understanding of multi-scale biogeophysical and chemical processes but also the integration of complexity science with social and humanistic disciplines.

In 2019, Professor Lenton's team reported in *Nature* that 9 out of 15 global climate tipping points had already been activated, namely the dieback of the Amazon rainforest,

[16] Lenton T M, Held H, Kriegler E, et al. Tipping elements in the Earth's climate system. *Proceedings of the national Academy of Sciences*, 2008, 105(6): 1786-1793.

collapse of Arctic sea ice, weakening of the AMOC, increased wildfires and pest outbreaks in North American boreal forests, global coral reef die-offs, accelerated ice loss from the Greenland Ice Sheet, thawing of boreal permafrost, accelerated ice loss from the West Antarctic Ice Sheet, and the collapse of the East Antarctic Ice Sheet [17]. Critically, breaching one tipping point can trigger domino effects through the internal feedback of systems. For instance, permafrost thaw releases additional greenhouse gases, exacerbating ice sheet loss, ocean acidification, and coral reef die-offs. These long-term irreversible changes pose severe threats to sustainable socio-economic development [18]. In their study published in *Science* in 2022, Professor Lenton's team advanced that current global warming of 1.1°C has pushed several tipping points into the "likely already crossed" range, including the collapse of the Greenland and West Antarctic ice sheets, mass mortality of tropical coral reefs worldwide, and thawing of Northern Hemisphere permafrost [1]. Professor Lenton pointed out that we have delineated substantial uncertainty ranges, but (some tipping elements) are unequivocally in the danger zone. We may be witnessing the onset of larger-scale tipping point activation, we hope not, but the probability is escalating [19].

Consequently, research on CEAC has become both critically important and urgently needed. Since the turn of the 21st century, scientific interest in this field has grown exponentially, with a corresponding rapid increase in publication output (Figure 1). As of December 2023, the top five countries by research publication volume in this domain include the United States, the United Kingdom, Australia, China, and Canada (Figure 2). The research focus in the field is undergoing a paradigm shift from primarily explaining phenomena to developing predictive capabilities and management strategies. In April 2023, the China Meteorological Administration highlighted the research on

[17] Lenton T M, Rockstrm J,Gaffney O.,et al. Climate tipping points:too risky to bet against. *Nature*.2019. 575(7784):592-595.

[18] Cai, R., Wang, H., Zheng, H., et al. Action against climate tipping points: carbon neutrality (in Chinese). *China Population,Resources and Environment*. 2021,31(09):16-23.

[19] Liu, D. Climate Tipping Points Approaching: Irreversible Impacts and Positive "Turning Points" (in Chinese). *The Paper of New Peach Uptide*. 2022-09-23 https://www.thepaper.cn/newsDetail_forward_20012845

climate tipping points published in *Science* and other leading journals, which revealed critical climate change risks, as one of its "Top 10 scientific breakthroughs in the field of climate change of 2022".

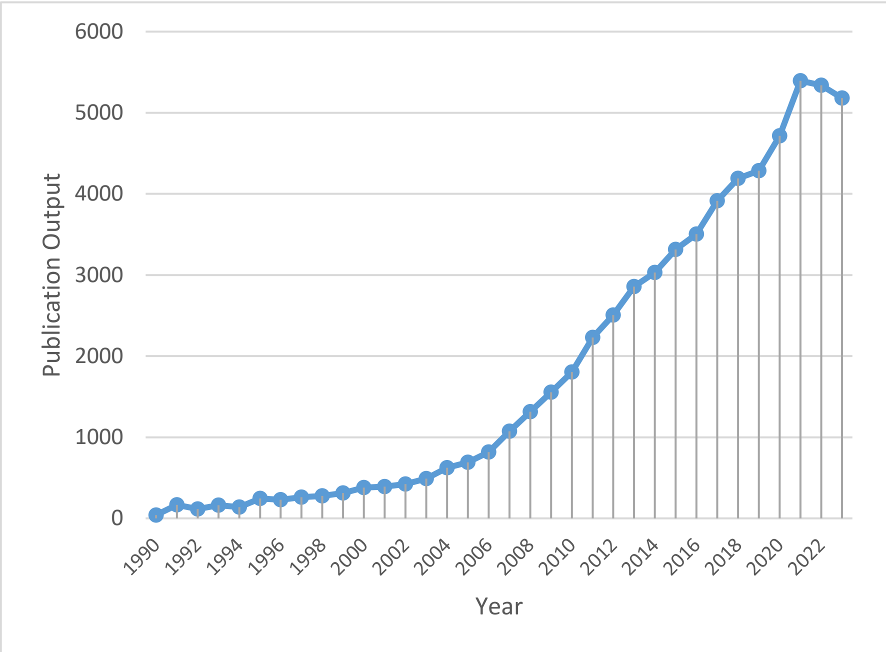

Figure 1 Growth curve of SCI paper output in the field of CEAC over the past 30 years.

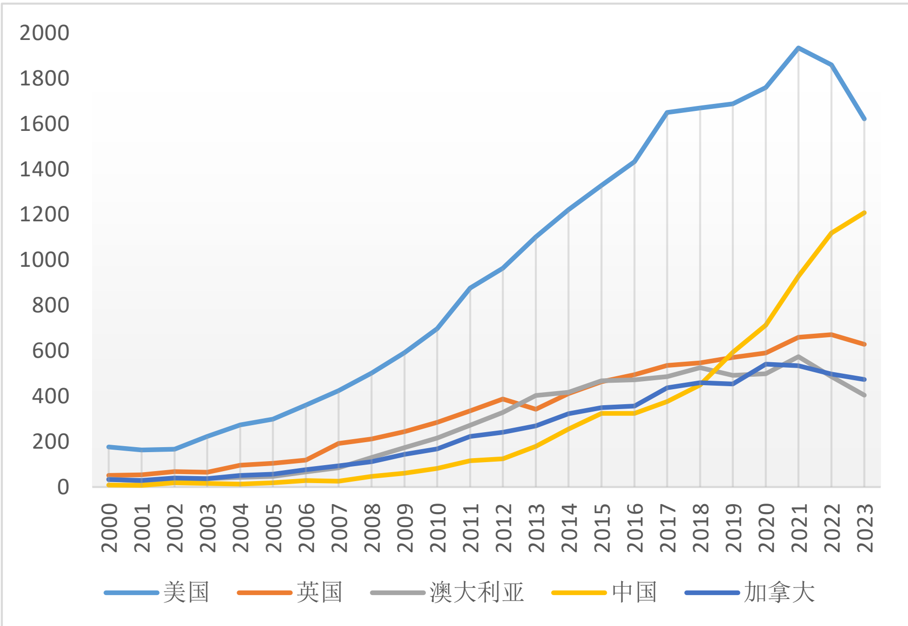

Figure 2 Growth curve of SCI paper output from major countries in the field of CEAC over the past 30 years.

Indeed, tipping points vary significantly across global climate and ecosystems, with their underlying mechanisms not yet fully understood. Moreover, divergent perspectives persist regarding the current understanding of tipping points. As research advances, particularly with a growing academic focus on global warming, the conceptual framework of abrupt changes has expanded. Recent research has led to a paradigm shift in scientific understanding: virtually all gradual changes may ultimately trigger abrupt shifts, with thresholds being dynamic rather than fixed, contingent on the interplay of multiple factors. While abrupt changes exhibit resilience properties, the spatial-temporal boundaries and mechanistic underpinnings of this resilience remain poorly constrained. Additionally, temporal dynamics play a pivotal role in CEAC.

2.2. Multi-scale, Multi-level, and Multi-method Research Approaches

Research on CEAC spans multiple scales, characterized by extensive temporal ranges and diverse spatial dimensions. From a spatial perspective, climate change research encompasses watershed, regional, and global scales, while ecosystem studies span hierarchical levels from species and populations to communities and entire ecosystems. Methodologies diverge across these scales but increasingly exhibit cross-scale integration and growing complexity trends.

In studying ecological abrupt changes at the population or community scales, controlled simulation experiments are widely employed. These involve manipulating specific environmental drivers to induce system transitions, with staged observations identifying regime shifts. For instance, a controlled chemostat experiment with cyanobacteria subjected to progressively increasing light stress, coupled with periodic minor disturbances, quantified biomass dynamics through light attenuation measurements, while indirectly assessing recovery rates of cyanobacteria. This experiment demonstrated the existence of tipping points for system abrupt changes and alternative states and revealed that moderate light intensity promotes cyanobacterial growth, while the resulting self-shading creates a positive feedback loop that further enhances biomass. However, excessively high light intensity proves detrimental to cyanobacterial growth, thereby establishing the mechanistic basis for alternative states. Furthermore, researchers can quantify abrupt changes by analyzing temporal biomass variations across species/communities or by focusing on indicator species that reliably signal ecosystem transitions. Integrating tipping point theory with network structural patterns enables the derivation of critical transition metrics. For example, Dakos et al. [20] investigated a 79-species mutualistic network under a scenario of gradual environmental change, observing that the system first experienced an abrupt extinction of a single species, followed by cascading extinctions culminating in complete community collapse. Their results demonstrated that the initially extinct species exhibited the highest coefficient of variation, while the nested architecture of the mutualistic network significantly increased the probability of regime shift.

At the ecosystem scale, common methodologies include large-scale simulation experiments and vulnerability structure analyses. Carpenter et al. [21] conducted a three-year comparative study monitoring two adjacent lake ecosystems, one experimentally manipulated through the gradual introduction of apex predators to disrupt the food web, while the other served as an undisturbed reference. The results demonstrated detectable early-warning signals preceding ecosystem regime shifts in the experimental lake. Vulnerability structural analysis at this scale reveals two fundamental system response characteristics: component heterogeneity and connectivity, whose influence on stability is mediated by the nature of network interactions. Systems exhibiting high nodal response heterogeneity and low connectivity tend to respond to environmental changes gradually rather than abruptly, as reduced resistance allows sequential regime shifts across individual nodes. In contrast, networks with homogeneous nodes and high connectivity often demonstrate transitional resistance until reaching a critical threshold,

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[21] Carpenter S R, Cole J J, Pace M L， et al. (2011) Early warnings of regime shifts: a whole- ecosystem experiment. *Science*, 332(6033): 1079-1082．

beyond which near-synchronous regime shifts occur across all nodal components.

From the perspective of broader spatial scales, research approaches diverge significantly between regional and global scale analyses.

At the regional scale, space-for-time substitution and satellite remote sensing are commonly employed to monitor ecosystem abrupt changes. However, the space-for-time approach has inherent limitations in predicting regime shifts in response to climate change. For instance, in terms of soil properties, significant spatiotemporal asynchronies exist between climate change, vegetation dynamics, and responses. Satellite-based monitoring, as an alternative method for predicting and validating regime shifts, primarily utilizes two analytical frameworks: (1) the hybrid methodology combining visual interpretation with computer-automated classification of remote sensing imagery, and (2) time-series comparative analyses employing statistical modeling of remote sensing-based indicators and their derivatives.

At the global scale, research on ecosystem abrupt changes predominantly employs model simulations or integrated approaches combined with worldwide field surveys and remote sensing observations. Studies investigating paleoclimate and mass extinction events have demonstrated that the most effective methodology involves reconstructing the temporal sequences of paleoclimate events through modeling, followed by validation of regime shift. A seminal example is the abrupt transformation of the Sahara approximately 5,000 years ago from a rich vegetated region with lakes into its current desert state. Dakos et al. [20] reconstructed temporal sequences of eight paleoclimate abrupt changes from geological records, employing simple climate models to simulate Earth’s transition from greenhouse to icehouse states.

Generally, quantitative analyses of ecosystem abrupt changes remain predominantly feasible at smaller scales, where experimental identification of tipping points is tractable. As spatial scales increase, predictability diminishes significantly, particularly due to the impracticality of controlled experimentation to identify the tipping point, necessitating a shift toward integrated approaches combining modeling with remote sensing observations to explore regime shift characteristics.

Given the inherent complexity and vast spatiotemporal scales of the climate system, most research on abrupt climate changes employed the integrated method with paleoclimate records, satellite and field observations, and climate modeling. On interannual-to-decadal scales, instrumental and satellite datasets provide robust evidence for detecting abrupt climate changes. Climatologists analyzed the abrupt climate change on surface temperature, atmospheric pressure, precipitation, and other meteorological variables based on diverse detection methodologies [22][23]. For longer timescales, paleoclimate studies on abrupt climate change through proxy-derived time series from ice cores, lake/marine sediments, pollen assemblages, tree rings, and animal fossils, which archive a wealth of long-term information on past climate change [24][25]. For instance, the well-established relationship between oxygen isotope ratios ($\delta^{18}O$) in ice cores and atmospheric temperatures offers the possibility to reconstruct past atmospheric temperatures and infer past climate conditions [26]. Greenland ice core $\delta^{18}O$ records retrieved in the 1990s revealed that temperatures during the last interglacial period exceeded present values by ~5°C, demonstrating how Northern Hemisphere ice extent regulates the meridional change of temperature in Greenland [27]. Dansgaard & Oeschger identified recurrent, abrupt climate oscillations in $\delta^{18}O$ records of ice core, termed Dansgaard-Oeschger (D-O) events [28]. Similarly, speleothem $\delta^{18}O$ variations, governed by moisture source dynamics and local precipitation amounts, archive

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changes in atmospheric circulation and convective intensity. Cruz et al. [29] leveraged this proxy to demonstrate the Dansgaard-Oeschger cycle impacts on the water cycle in subtropical southern Brazil.

The acquisition of paleoclimate information by humans is indirect, mainly through proxy indicators such as physical parameters (e.g., magnetic susceptibility and grain size), chemical parameters (e.g., elements), and/or biological fossils (e.g., foraminifera, spore pollen) that respond to climate change to reconstruct past climate change. However, these environmental proxies are imperfect climate archives with inherent uncertainties. For instance, ice core records of Greenland and Antarctica suggested synchronous millennial-scale temperature variations between hemispheres during the last glaciation, contradictory evidence from the Ross Sea sector of East Antarctica indicated hemispheric asynchrony [30]. While transfer functions and other quantitative paleoclimate reconstruction methods enable direct comparison with model simulations, their inherent uncertainties may lead to erroneous interpretations, thus imposing fundamental limitations on using paleoclimate proxy data for both paleoclimate indication and model evaluation. Climate models generate direct outputs of Earth system variables (e.g., temperature, wind speed, precipitation), making the effective integration of paleoclimate data and climate simulation results critical. Three key steps can address paleoclimate-model integration challenges: (1) selecting the appropriate chemical tracing method related to the indicator record; (2) clarifying the climatic-environmental significance of proxy indicators; (3) integrating analytical approaches of paleoclimate records and model data. For instance, the high-resolution deuterium (δ^2H) profile in ice core obtained from the European Project for Ice Coring in Antarctica (EPICA) and an atmospheric general circulation model including water isotopes collectively revealed the variable intensity of temperature associated with Dansgaard-

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Oeschger events [31].

Simplified climate models are essential tools for investigating the processes and mechanisms of abrupt climate change. These models conceptually distill the complexity of the climate system into simplified dynamic processes. By systematically varying control parameters, they solve for changes in the system's equilibrium (e.g., number and stability), thereby revealing the physical mechanisms underlying regime shifts [32]. For instance, classic box models have been used to analyze the equilibrium of the Atlantic Thermohaline Circulation in response to high-latitude freshwater inputs on millennial timescales [33]. Similarly, Levermann et al. [34] developed a conceptual model based on the balance between the monsoon precipitation latent heat, land-sea thermal advection, and radiative forcing. Their study identified critical irradiance thresholds for monsoon system collapse, revealing that current climate conditions in India and North America are approaching the tipping point of monsoon collapse.

With continuous advancements in computer performance and model resolution, along with refined parameterizations of physical processes, climate models have served as effective tools for investigating critical transitions and mechanisms of climate systems across multiple spatiotemporal scales. Diverse climate models spanning a spectrum of complexities are now routinely deployed to investigate abrupt climate change events and critical transitions. For example, North [35] employed an energy balance model incorporating ice-albedo feedback and thermal diffusion processes, demonstrating that Arctic ice sheet dynamics under solar constant variations exhibit bistability—with two stable equilibrium states. Zhiyuan Wang [36] conducted a 2000-

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year global climate simulation using the Community Earth System Model (CESM), detecting and analyzing the shift timing and driving mechanisms of centennial-scale surface temperature worldwide.

Beyond critical transition within individual climate subsystems, cascading effects can propagate across climate subsystems through atmospheric and oceanic circulation responses. Current research methodologies combine dynamic systems with network approaches, integrating expert-derived experience knowledge of tipping point properties with causality from logical inference to analyze these climate subsystem interactions [37]. Based on a conceptual network model, Wunderling [38] assumed that the Greenland Ice Sheet, West Antarctic Ice Sheet, AMOC, and Amazon rainforest all exhibit bistability with saddle-node bifurcations, incorporating linear couplings to explore interactions among these four subsystems. The results demonstrated that Greenland ice loss would trigger cascading effects under global warming, with the AMOC serving as a transmission pathway to other subsystems. Liu et al. [39] established a climate network statistical model using daily global surface temperature data, identifying robust teleconnections between the Amazon rainforest and the Tibetan Plateau, as well as the West Antarctic Ice Sheet through cross-correlation analysis. Their findings revealed synchronized abrupt changes across these climate subsystems. The climate system exhibits profound complexity across vast spatial and temporal scales. Studies of its abrupt changes predominantly employ integrated methodologies combining paleoclimate records, satellite and ground-based observations, idealized conceptual analyses, and climate modeling.

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2.3. Data as a Critical Element for Future Research

The data revolution is driving two transformative shifts in Earth science research: a paradigm shift from problem-driven to data-driven research, and a transition from expert-based analysis to machine learning and AI-powered approaches [40]. Under this data-driven paradigm, data has become a critical element, therefore significantly altering data observations, acquisition, analysis, and usage methods. Research on CEAC, encompassing assessment, modeling, and prediction, fundamentally depends on high-quality data. Consequently, how to obtain long-term, precise data has emerged as a critical issue in this field, necessitating scale-appropriate methodological selection.

Earth science research has undergone a dramatic expansion on spatiotemporal scales, driven by evolving scientific understanding and research requirements for the Earth, as well as technological advancements and new method introductions. CEAC studies now span timescales from instantaneous events to multi-million-year scales, and spatial scales from local habitats to the whole Earth system. Establishing integrated, sustainable cross-scale observation and data acquisition systems is fundamental significance of understanding the climate and ecological systems. Laboratories, field observation stations, aerial platforms, and Earth observation satellites serve as critical infrastructure for observation and detection to obtain primary data and enable innovative research in this field.

In ecosystem research, traditional data acquisition methods are characterized by small spatial scales and high accuracy but are time-consuming and labor-intensive. At large spatiotemporal scales, conducting repetitive and controlled experiments is neither practical nor feasible. Moreover, insights derived from small-scale ecological processes and patterns are often insufficient to fully and comprehensively explain ecological

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phenomena at broader scales, such as landscape or global scales[41][42]. Remote sensing is the only technical method that can effectively obtain real-world data on a large scale [43][44]. It serves as a critical data source for research in the field of CEAC and is an essential tool for the assessment, simulation, and prediction of these changes.

Compared to traditional ground-based surveys, remote sensing offers significant advantages for monitoring ecosystem abrupt changes, particularly in arid zones and forests, due to its rapid, multi-spectral, periodic, and large-scale observational capabilities. As a key technology for expanding ecological research from single-point to regional scales, remote sensing not only supplements ground-based monitoring but also has the potential to replace certain field measurements in modern ecological studies [45]. Remote sensing enables the acquisition of diverse, long-term surface parameters on a large scale, including various vegetation indices (e.g., NDVI, EVI, SAVI), fractional vegetation cover, surface albedo, and surface soil moisture. These datasets serve as essential inputs for assessing ecosystem states. In recent years, the application of remote sensing technology has expanded across diverse fields including meteorological observation, territorial mapping, ocean monitoring, disaster monitoring, and environmental monitoring. This growing demand has driven continuous technological advancements, leading to improvements in the spatial, temporal, and spectral resolution of remote sensing data. Concurrently, China has significantly increased its launches of Earth observation satellites.

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2.4. Detection Methods and Early-Warning Technologies for CEAC

Accurately identifying and detecting abrupt changes is crucial for predicting the future evolution of climate and ecological systems. Traditional detection methods, such as moving t-tests, Cramer's method, Yamamoto's approach, and Mann-Kendall tests [35], primarily rely on statistically significant shifts in state variables, making them unsuitable for monitoring structural shifts in the dynamics of climate and ecological systems. In recent years, several newly developed methods for detecting abrupt changes in climate dynamics have shown potential for application. For instance, the evolution of the climate system exhibits long-range correlations, which manifest in meteorological variables such as surface temperature, atmospheric pressure, and precipitation, as well as in the recurrence intervals of extreme events. Various detection methods based on the long-range correlation properties, including moving detrended fluctuation analysis, moving cut detrended fluctuation analysis, moving cut data-rescaled range analysis, moving cut data-rescaled variance analysis, detrended fluctuation-based fingerprinting, and red-noise testing, show promise for monitoring and detecting CEAC [46][47][48]. Another viable approach is the use of approximate entropy and information entropy methods to assess the complexity of time series data[49][50]. The approximate entropy technique is an ideal nonlinear dynamical detection method, requiring relatively few data points while demonstrating strong

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resistance to noise and interference. It applies to both random and deterministic signals, as well as their mixed forms. Cheng et al. [50] pioneered the application of approximate entropy to abrupt climate change detection by developing the moving cut approximate entropy method and validated the reliability of this method by employing precipitation observation data. Meanwhile, Fisher et al. [51] developed a statistical measure of uncertainty called Fisher information, which assesses parameter estimation capacity and can detect state transitions of systems or phenomena. Additional promising approaches include dynamical exponent segmentation algorithms for spatial fields and modal correlation method [52][53]. The latter is widely used in climate change research for investigating the potential driving mechanism of climate change, including distinguishing the roles of human activities and natural variability [54].

Detecting early-warning signals for CEAC and understanding the underlying dynamics of state variables as systems approach tipping points are of great significance. Critical slowing down and flickering phenomena serve as the most critical early-warning signals for impending critical transitions in climate systems. The critical slowing down phenomenon occurs when the control parameters of a dynamic system approach a tipping point, and the real parts of the Jacobian matrix's eigenvalues of the system converge toward zero from negative values. According to the equilibrium stability analysis, the superimposed small disturbances will decay exponentially at a slow rate with prolonged recovery time, leading to the phenomenon characterized by the increased autocorrelation coefficient and variance of the time series of the dynamic system state parameters before the tipping point increase, along with the decreased

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skewness. Dakos et al. [55] examined eight abrupt paleoclimate change events, such as the termination of the Younger Dryas, North African desertification, and the last glacial termination, demonstrating that critical slowing down consistently preceded these transitions with increased autocorrelation in time series before shifts. Consequently, critical slowing down has been mathematically proved as a robust signal of climate systems approaching tipping points. As the control parameters of a dynamic system approach a critical point, critical slowing down leads to a decrease in the skewness of the probability density distribution of state variables in the time series [56]. If the stochastic forcing is sufficiently strong, the system will switch between two (or multiple) stable equilibrium states. This manifests as a bimodal (or multimodal) probability density distribution of state variables, along with a decrease in the first-order autocorrelation coefficient and an increase in variance in the time series—phenomena collectively known as flickering. For instance, Bakke et al. [57] analyzed lake sediment core records and reconstructed ocean paleo-temperature/salinity data, revealing that the ocean and atmosphere system oscillated between two equilibrium states before the Younger Dryas termination, and finally transitioning to the warmer Holocene epoch. This evidence underscores that critical slowing down and flickering phenomena serve as vital diagnostic tools for assessing whether complex dynamic systems are approaching tipping points [3].

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3. Key Scientific Issues and Core Technical Challenges

Based on the principles of scientific rigor, fundamental importance, and feasibility, this study examines key scientific questions and core technological challenges following the logical framework of "spatiotemporal processes of resilience change – tipping thresholds and mechanisms of abrupt changes – scientific identification of abrupt changes – early warning and prediction." Specifically, it includes:

3.1. Processes, Modes, and Patterns of CEAC

3.1.1. Interactions of Climate and Ecosystem Abrupt Change Across Different Scales

(1) What are the patterns of abrupt changes in climate and ecosystems at different spatial and temporal scales, in particular the interactions among various elements during these abrupt changes?

Abrupt climate change may occur across interannual, decadal, centennial, millennial, and even longer timescales, underscoring the need to identify their thresholds, signatures, and patterns at different timescales. A particularly critical aspect is understanding the transient dynamics during critical climate transition periods and the hierarchical interactions between abrupt changes occurring at different timescales—both of which represent key breakthroughs in abrupt climate change research. In ecosystems, abrupt shifts and reorganizations can occur at all levels, from species and populations to communities and entire ecosystems, inevitably driving profound changes in species composition, biomass, productivity, functional traits, and the dominance of keystone species. What relationships exist between abrupt change thresholds across these hierarchical levels, and how do they interact with each other? For instance, how the abrupt change of a single population may cascade to alter other communities' abrupt shifts, ultimately triggering system-wide regime shifts that propagate as large-scale ecological cascade reactions.

(2) What are the cascading effects and remote coupling relationships between

abrupt changes at different spatial and temporal scales?

Across spatial scales, from watersheds and regional systems to the global scale, climate and ecosystems exhibit distinct threshold ranges and abrupt change characteristics. However, the cascading effects and long-range coupling relationships between these abrupt changes remain unclear. Therefore, it is crucial to elucidate the processes, characteristics, and patterns of abrupt changes in typical ecosystems, such as grasslands, marine systems, and wetlands, under the same context of climate change or anthropogenic disturbances. A systematic comparison of their differences in abrupt change and underlying mechanisms will provide novel theoretical insights to support research on abrupt changes.

3.1.2. Quantitative Research on the Resilience and Thresholds of CEAC

(1) How can we quantify changes in system resilience and tipping points to reveal the characteristics and patterns of abrupt changes in the climate and ecological system?

Climate and ecological systems may undergo abrupt changes or regime shifts when declining resilience pushes them beyond thresholds or tipping points. Current research primarily focuses on analyzing dynamic characteristics of system changes through time-series data, such as variance, autocorrelation, and slope, to semi-quantitatively reveal changes in resilience. Furthermore, various statistical and mathematical models are employed to identify thresholds of system abrupt changes based on changes in the mean or variability of time series. How can we analyze the relationships among system structure, function, biodiversity, and connectivity with resilience and abrupt change from a mechanistic perspective? How to reveal the system resilience based on ecosystem structure and functions, thereby deepening the understanding of patterns and characteristics of abrupt changes? Furthermore, how can we develop an integrated indicator system to quantify resilience and abrupt change, enabling cross-ecosystem comparisons of resilience dynamics? These questions represent the core challenges, frontiers, and potential breakthroughs in current research.

(2) How can we effectively integrate short-term monitoring data with paleoenvironmental data, and combine multi-disciplinary research methods such as model simulations, to quantitatively determine the tipping points and resilience of CEAC at different spatial and temporal scales?

Current research in this field primarily relies on observations, controlled laboratory experiments, and model simulations. However, these approaches face significant limitations: short temporal scales often fail to capture the entire process before and after abrupt system shifts, and there is a lack of long-term real-world data for effective validation. As a result, explanations of resilience and abrupt change theories remain highly debated and uncertain. A key challenge is how to leverage the advantages of long-term paleoenvironmental records, particularly by extracting high-resolution, precisely dated, and mechanistically well-constrained biological proxy records. These records can provide critical insights into past climate and ecosystem evolution across different climatic conditions and ecological settings, thereby offering essential data support for reconstructing past Earth system trajectories and deciphering the patterns and mechanisms of CEAC.

3.2. Research on the Mechanisms of CEAC

3.2.1. Mechanisms of Abrupt Changes Driven by Multiple Stressors

(1) How to deeply reveal the driver-response relationships, particularly clarifying the driving mechanisms of linear gradual changes and nonlinear abrupt changes?

CEAC results from the long-term cumulative effects of multiple stressors. Theoretically, the interactions among various driving forces can have three distinct effects on a system: additive, synergistic, or antagonistic relationships. For instance, the combined influence of temperature and nutrient availability on aquatic ecosystems may lead to additive, amplified, or even weakened impacts. Thus, clarifying ecological response relationships to multiple drivers is critically important. Furthermore, a fundamental scientific question persists: Why do some systems exhibit linear, gradual changes driven by multiple stressors, while others undergo abrupt changes? What determines whether a system follows a gradual trajectory or crosses a critical threshold? Which abrupt changes are triggered by rapid external forcing, and which arise from internal structural and functional shifts within the system? These questions represent fundamental and pressing research priorities in the current relevant field. In particular, when reconstructing past climate and ecosystem dynamics, it is essential to account for such nonlinear driver-response relationships and avoid overly simplistic linear reconstructions and interpretations. A more systematic and comprehensive approach is needed to accurately capture the complex dynamic interactions between climate and ecosystems.

(2) What is the process of abrupt changes in the system under the long-term interaction of multiple driving forces?

Previous research indicated that the interplay between fast and slow drivers can trigger ecosystem abrupt changes. For instance, while gradual increases in nutrient loading and temperature progressively weaken ecosystem resilience, rapid drivers, such as extreme weather events, floods, or dam construction, often act as a final “straw” that pushes the system across its critical threshold. Additionally, ecological responses often exhibit time-lag effects and cascading reactions, significantly complicating the study of mechanisms underpinning CEAC. Therefore, a sufficiently extended temporal scale is required to accurately elucidate the complex relationships between diverse drivers and system responses, thereby enabling in-depth revelation of the processes and mechanisms underlying abrupt changes.

3.2.2. Feedback Mechanisms and System Abrupt Changes

How can we elucidate the feedback and interactions among different climate and ecological systems, particularly the changes in positive and negative feedback mechanisms over long-term variations?

The alteration of positive/negative feedback mechanisms within climate and ecosystems constitutes a pivotal factor driving regime shift. Negative feedback stabilizes system dynamics, whereas amplified positive feedback drives system instability. The state of a system emerges from the long-term interplay between these positive/negative feedback mechanisms. Crucially, when climate and ecosystems undergo abrupt changes or regime shifts under driving forces, the dominance of novel positive feedback loops over negative ones accelerates the state transitions. For instance, declining temperatures accelerate glacier formation, which increases surface albedo and further reinforces cooling, establishing a self-amplifying positive feedback loop. Similarly, when ecosystems undergo regime shifts, their reorganized structure and functions fundamentally alter internal feedback mechanisms. This modification can push the system across critical thresholds, triggering abrupt changes. Consequently, it is imperative to integrate multi-method approaches, including observational studies, laboratory-controlled experiments, modeling simulation, and long-time series analyses, to elucidate alterations in feedback mechanisms both within and across systems.

3.3.Identifying Key Tipping Elements of CEAC

3.3.1. Tipping Elements

How can we accurately identify the critical elements of the Earth system and determine their tipping points?

Current research highlights the Earth system's abrupt change as a pivotal factor in addressing global climate change, drawing significant international attention. As reported in *PNAS*, nine potential climate tipping elements within the Earth system have been identified under ongoing climate change. Subsequent studies published in *Nature* and *Science* expanded this list to 16 tipping elements, indicating that the tipping points of some tipping elements such as the Amazon rainforest, Arctic sea ice, Atlantic Meridional Overturning Circulation, Australian coral reefs, and Greenland Ice Sheet may already have been triggered. These tipping elements are not static but dynamically evolve alongside climatic and ecological changes, making their identification a pressing scientific challenge. Equally critical is determining the temperature thresholds associated with these tipping elements.

3.3.2. Key Tipping Elements in China

How can we identify the key critical elements in China and reveal their mechanisms of abrupt changes? How can we assess the current system's risk of abrupt changes?

The theoretical framework of tipping elements (or tipping points) was initially proposed by Western scientists and did not fully account for Earth system dynamics in critical regions like China. Questionnaire-based research indicates that China's Earth system tipping elements with relatively high consensus include: the Tibetan Plateau, human activities, arid and semi-arid regions, and the East Asian monsoon. Specifically, the Tibetan Plateau involves critical components such as glaciers and permafrost; human activities primarily focus on urbanization and industrialization; arid and semi-arid regions are of concern due to issues like soil desertification; the East Asian monsoon refers to rapid shifts in summer and winter monsoons, driving extreme climate events. Additionally, a minority of respondents identified forest ecosystems, biodiversity, and lake ecosystems as potential tipping elements within China's Earth system.

Building upon this foundation, our research team has conducted further studies and identified the following key tipping elements within China's Earth system: thawing of permafrost, accelerated melting of alpine glaciers, variability in the East Asian monsoon, the Western Pacific Warm Pool, greening of northwestern arid and semi-arid regions, transformation of boreal forests, desertification of Mongolian grasslands, and degradation of mangrove ecosystems. For these tipping elements, how to identify their precise thresholds and elucidate the underlying mechanisms driving these abrupt changes warrants in-depth exploration.

Undoubtedly, changes in these tipping elements will have profound impacts on ecosystems both in China and globally. Against the background of global warming, critical questions emerge. Will the Asian monsoon climate system undergo abrupt changes in the future, and how would such changes alter temperature and precipitation patterns across East Asia? Particularly after warming of +1.5°C, which ecologically sensitive regions in China face heightened risks of abrupt changes? How to identify the critical tipping elements in China's ecological environment and climate systems? For instance, what are the current historical phases of ecosystems such as the Tibetan Plateau system, the arid grassland ecosystems of Northwest China, and freshwater ecosystems, and what are the potential risks of abrupt changes they may face in the future? Which systems are most likely to undergo systemic abrupt changes? Providing scientifically robust answers to these questions holds critical scientific value and strategic significance for China's ecological security, water security, and food security. Therefore, there is an urgent need to conduct integrated paleo-modern research to reconstruct the historical trajectories of abrupt changes in the Asian monsoon climate system and China's representative ecosystems across diverse spatiotemporal scales, and identify China's critical tipping elements and systematically assess current risks of systemic abrupt changes by synthesizing modern observations, remote sensing data, and model simulations.

3.4. Assessing and Predicting Ecosystem Security and Risks of Abrupt Changes Under Climate Warming

3.4.1. Simulation of Ecosystem Abrupt Changes and development of Early Warning Systems

How can we scientifically predict the risks of future climate and ecological abrupt change events and take mitigation measures?

The *Early Warnings for All Executive Action Plan (2023-2027)* released at COP27 - the United Nations Climate Change Conference in 2022 emphasizes the need to address existing gaps in the global climate observation system and enhance capabilities to provide actionable climate information for mitigation, adaptation, and early warning systems. The climate system, characterized as a nonlinear dynamic system with complexity and openness, poses significant challenges in predicting abrupt climate change. Current climate and ecosystem models in China exhibit notable deficiencies in simulation capabilities, necessitating urgent advancements. Critical technical challenges that must be addressed in the next step include: 1) developing coupled system dynamics models that adequately incorporate complex system features such as multi-dimensional driver-response relationships, positive/negative feedback mechanisms, time-lag effects, cascading impacts, and emergence; 2) conducting multi-scale simulations across climatic, ecological, and societal dimensions to elucidate abrupt change processes and mechanisms within complex systems; and 3) predicting future risks of abrupt changes in climate and ecosystems.

Generally, climate and ecosystem modeling and early warning represent an emerging research direction that has rapidly developed over the past decade. It encompasses multiple temporal scales (spanning millions of years to days) and three dimensions: climate, ecology, and society. Compared with international counterparts, China's capabilities in climate and vegetation ecological modeling are generally on par. However, urgent advancements are needed in developing dynamic vegetation models, marine biogeochemical models, and socio-economic demographic models. The true challenge in climate-ecosystem modeling and early warning lies not in technical aspects, but in achieving interdisciplinary integration and breaking down disciplinary barriers.

3.4.2. Establishing Safe Operating Spaces for Typical Ecosystems in China

How can we identify the tipping points and boundary ranges of different ecosystems under the combined influence of climate and human activities, as well as the ecological safety space of typical systems?

In response to the increasing risks of ecosystem abrupt changes worldwide, formulating scientific ecosystem protection and management strategies to mitigate potential catastrophic risks and safeguard ecosystem service functions constitutes a major challenge for both the scientific community and policymakers. Furthermore, there is an urgent need to establish an early warning indicator system for abrupt changes to effectively predict catastrophic events. For ecosystems that have already crossed critical thresholds and undergone abrupt changes, developing restoration strategies based on long-term dynamic trajectories, intrinsic characteristics, and driver-response relationships to restore them to safe operational boundaries holds vital implications for ecological rehabilitation and governance. Therefore, policy formulation should actively explore approaches rooted in complex systems perspective and fully account for abrupt change and thresholds, to transition from traditional static management paradigms toward dynamic management frameworks that prioritize maintaining system resilience and thresholds.

3.4.3. Addressing CEAC and Promoting Sustainable Development

(1) How can we effectively respond to CEAC?

China is recognized as one of the world's most climate-sensitive and significantly climate-impacted regions. Climate change poses severe challenges to multiple fields in China, including food security, public health, water resources, ecological environments, energy systems, major infrastructure projects, and socio-economic development, with the escalating climate risk levels across these domains[58]. In June 2022, China's *National Climate Change Adaptation Strategy 2035* outlined that climate adaptation efforts should adhere to the principles of "active adaptation by putting prevention first, scientific adaptation by following the laws of nature, systematic adaptation by highlighting priorities, and collaborative adaptation by coordinated and cooperative governance". Currently, mitigation and adaptation represent the two fundamental pathways for addressing climate change. Climate change mitigation, achieved through emission reductions and enhanced carbon sequestration, aims to control the net emissions of greenhouse gases into the atmosphere, serving as the foundational approach to tackling climate change. Climate change adaptation involves adjusting

[58] China Meteorological Administration Climate Change Centre. Blue book on climate change in China (2021) (in Chinese), 2021, Beijing: Science Press.
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natural and human systems to respond to actual or projected climate change impacts, mitigating or avoiding associated harms—for example, through measures like building “sponge cities”. For more abrupt and impactful climate-ecosystem changes, we must proactively explore pathways to address these critical challenges.

(2) How can we harness the positive impacts of abrupt changes while mitigating the negative impacts?

Abrupt change is not solely detrimental; a single abrupt change event may yield divergent impacts across regions. Our research must actively address how to mitigate the negative effects of abrupt changes by leveraging the positive impacts, which constitutes a priority focus for subsequent scientific research.

4. Safeguard Measures

Research in the field of CEAC requires the prioritization of long-term integrated observational capabilities, robust mechanisms for data and resource sharing, interdisciplinary collaboration, and cultivating innovative talent. These measures collectively form the foundational safeguards necessary to drive field breakthroughs in addressing CEAC.

4.1. Data Observation Platforms and Data Analysis Technologies

In the field of CEAC, it is crucial to establish long-term and stable data observation platforms. This requires strengthening the deployment of observation systems by establishing permanent monitoring stations and enhancing empirical data collection, thereby expanding reliable remote sensing data sources for climate and ecological change monitoring. Clear identification of deficiencies in current observation systems across different spheres should be followed by creating an integrated, interconnected, and standardized observation network focusing on sea-land-atmosphere interactions. Efforts should be made to promote the development and application of next-generation Earth observation technologies such as the Internet of Things (IoT), sensors, and remote sensing to establish a comprehensive all-weather continuous observation system that is capable of monitoring multi-sphere and multi-element Earth systems. To address the systemic, nonlinear, complex, and uncertain characteristics of climate and ecosystem abrupt changes and their risk processes, advanced technologies such as “deep-space”, “deep-earth”, and “deep-sea” exploration systems, combined with modern electronic sensing, should be fully leveraged. This will drive the development of “space-air-ground-sea” integrated, multi-dimensional coupling, and intelligently interconnected key technologies for risk perception and dynamic monitoring targeting various abrupt changes. By overcoming scientific bottlenecks in risk identification and monitoring, these innovations will establish a foundational information infrastructure for the risk prevention of abrupt changes.

CEAC involves multi-source data spanning diverse spatiotemporal scales. These datasets are collected from laboratories, field observation stations, airborne platforms, and Earth observation satellites. There is an urgent need to establish a foundational CEAC database by integrating expertise from leading domestic institutions, creating a long-term, stable data-sharing platform to enable open access to extended observational time series.

The construction of observation platforms has generated massive datasets for CEAC research. However, extracting and processing relevant variables from such datasets remains a critical challenge. It is imperative to develop GIS-based data analysis and application systems to achieve automated analysis, evaluation, and simulation of monitoring data, tailored to the characteristics of climate-ecosystem monitoring systems and data types, aligned with advancements in data communication, information technologies, and practical demands.

There is an urgent need to develop big data analytics and AI-driven predictive methodologies based on extensive field investigations, observational data, and analytical testing results to explore the relationship between climate change and ecological security. Strengthening the coupling of ecological processes and environmental indicators in models will enable the quantitative reconstruction of interactions and regulatory mechanisms among carbon cycling, climate change, environmental evolution, and biodiversity transformation in the Earth system. Additionally, it is crucial to establish an ecological abrupt change risk prevention system centered on proactive disaster prevention and mitigation. Key priorities include: developing process models and simulators to construct an abrupt change risk simulation system and scenario database; advancing high-precision, proactive forecasting and assessment of abrupt change risks; leveraging next-generation technologies—such as electronic sensors, modern communication systems, big data, and AI—to establish an all-weather, real-time dynamic monitoring and intelligent early-warning system for abrupt changes; designing specialized, multifunctional, portable, and intelligent emergency response and rescue equipment adaptable to extreme environmental conditions, ensuring effective and rapid intervention in abrupt change scenarios.

The climate and ecological system constitutes a complex system involving interdependent elements across multiple spatiotemporal scales, and different scales exist cascading feedback mechanisms. To better characterize this complex system and predict its changes, it is imperative to conduct multi-scale and multi-modal research. China currently lacks indigenous Earth System Models (ESMs), as existing models achieve only partial coupling of component systems. In the future, there is an urgent need to develop homegrown ESMs with multi-system coupling, aiming to advance coordinated breakthroughs in climate-ecosystem big data technologies, including mining, fusion, causal inference, and data assimilation, and master integrated coupling analytics to enhance capacities spanning problem diagnosis, mechanistic analysis, and long-term predictive capabilities.

4.2. Disciplinary Development, Talent Cultivation, and International Collaboration

CEAC is a comprehensive research topic that requires a systematic approach. Interdisciplinary collaboration serves as its fundamental premise. This necessitates institutionalizing interdisciplinary convergence mechanisms through permanent academic exchange platforms that facilitate the integration of climatology, ecology, geology, geography, mathematical science, information science, etc. At the institutional level, we propose establishing a Collaborative Innovation Center under coordinated governance by the Ministry of Science and Technology, the Chinese Academy of Sciences, or the National Natural Science Foundation of China to integrate China's scientific research backbone in the field of climate and ecology. In terms of project approval, major programs should be prioritized with funding mechanisms requiring mandatory interdisciplinary and interprofessional.

In recent years, China has made significant progress and advancements in climate and ecological research. In terms of the breadth of scientific research coverage, its role in national economic development, as well as the scale of education, and the number of scientists engaged in research, China can be considered a major player in climate and ecological studies. However, it has yet to establish itself as a global leader in these fields. The number of research areas and directions where China holds an international lead remains limited, and its global influence is still constrained. Moreover, there is a relative lack of groundbreaking, high-precision theories, methodologies, and technologies with strong originality. Most importantly, China faces a shortage of strategic scientists and innovative talent in these domains.

To address the research requirements in CEAC studies, it is essential to focus on cultivating diverse functional talents. This includes consciously nurturing strategic scientists who grasp the frontiers of the discipline, tactical scientists who drive cutting-edge exploration, and a young reserve talent pool to ensure the long-term, sustainable development of the field. Given that CEAC research involves complex systems, special attention should be paid to designing knowledge structures that foster expertise in emerging disciplines and interdisciplinary research. This will further promote the integration of related fields and contribute to the formation of national strategic scientific and technological capabilities. A well-structured talent pipeline with a balanced mix of senior, mid-career, and young scientists should be developed, with particular emphasis on strengthening the participation of young scientists. Additionally, international collaboration in the field of CEAC should be reinforced, leveraging global data platforms as bridges to address the strategic needs of the Belt and Road Initiative. A major international initiative on CEAC should be launched to foster extensive global collaboration and joint technological breakthroughs. This will drive original innovation in fundamental theories and technologies, position China as a leader in climate and ecological research, and push related technologies toward deeper and more advanced developments, ultimately serving the construction of ecological civilization in the new era.