On the Postprint of the New Era of Earth Science

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Abstract

Recently, climate change has emerged as a focal issue across the scientific community, government, and civil society. This article systematically examines how breakthroughs in technological tools for understanding nature have revealed the increasingly intensified impacts of human activities on the natural world. Since the Industrial Revolution, industrialization-driven urbanization has become the dominant driver of climate change, engendering profound transformations in both nature and human society. Due to its agglomeration effects, this process is now accelerating Earth' s changes at an unprecedented rate, placing the complex Earth system comprising natural and human societies in an increasingly severe state of crisis and threat. Research demonstrates that climate change and urbanization, while generating a host of challenges—including Earth system disruptions, resource-ecology-environment degradation, urban development pressures, public health risks, and social vulnerability—simultaneously create new demands and inject fresh momentum into Earth science, ushering the discipline into a new Anthropocene era. The article contends that the Anthropocene geological epoch necessitates a redefinition of Earth science. Earth science research will transition from a stratigraphy-centered approach to one focused on Earth spheres, expanding its objects and domains from purely geoscience systems to human-Earth coupled systems, and shifting its emphasis from Earth resource extraction to broad habitable planet research. Key new growth areas will include Anthropocene studies, anthroposphere geography, cryosphere science, hydrosphere-anthroposphere interfaces, Earth system dynamics, urbanization and urban geography, geoethics semiotics, and integrated Earth mapping. Geography, by virtue of its inherent status as the mother of all natural and social sciences, stands poised for renewed development and prosperity, with human geography capable of playing an increasingly vital disciplinary role.

Full Text

On the New Era of Earth Science

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Abstract

Recently, climate change has become a topic of intense interest in the scientific community, government agencies, and civil society. Beginning with a description of breakthrough technologies that have transformed humanity' s ability to understand nature, this paper systematically introduces how human impacts on the natural world have become increasingly pronounced. Since the Industrial Revolution, industrialization-driven urbanization has emerged as the dominant factor in climate change, bringing about tremendous transformations in both nature and human society. Due to the accelerating agglomeration effects of urbanization, Earth' s complex natural and human social systems are already facing increasingly severe crises and threats. Our research demonstrates that climate change and urbanization, on the one hand, generate a series of problems related to Earth systems, resources and environment, urban development, public health, and social vulnerability; on the other hand, they create new demands and inject new momentum into the development of Earth science, ushering it into a new era—the Anthropocene. This paper argues that the Anthropocene geological epoch necessitates a redefinition of Earth science. Earth science research will shift from being stratum-based to sphere-based, its objects and domains will expand from purely geoscience systems to human-Earth composite systems, and its focus will transition from resource extraction to the study of planetary habitability. The Anthropocene and its study, anthroposphere geography, cryosphere science, the hydrosphere-anthroposphere interface, Earth system dynamics, urbanization and urban geography, geoethics and semiotics, and EarthMAP integration will become new growth points for Earth science. Geography, with its inherent characteristic as the "mother of all sciences" —both natural and social—will encounter new opportunities for renewed development and prosperity, with human geography in particular poised to play an even more important disciplinary role.

Keywords: climate change; urbanization; accelerating change; Anthropocene; Earth science; geography; human geography

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1. Dating Technology and New Understanding of Earth Changes

1.1 Traditional Human Understanding of Nature

For a very long time, the traditional human understanding of nature held that human influence on nature was negligible and that humans were merely one component of the natural world. Scientists generally believed that Earth changes, particularly natural changes, occurred only over long geological timescales. The Milankovitch theory, which posits that glacial cycles are driven by variations in Earth' s orbit that alter seasonal heat balance, operates on timescales of tens of thousands of years. Even after Darwin' s theory of evolution, humans believed that natural evolution over ten-thousand-year timescales was minimal. As late as the early 20th century, climatologists still maintained that global climate was essentially unchanging. For any given region, climate conditions could be described using the average values of 30-year records.

1.1.1 Minimal Human Impact on Nature From the perspective of human impacts on nature, the 标志性 historical event was the use of tools, dating back approximately 3,000,000 years ago, known as the Old Stone Age. However, due to sparse populations and simple tools, human impacts on nature during that era were minimal. Some 40,000 years ago, Homo sapiens began using their extraordinary brains to adapt to their living environments and gradually attempted to modify them. The discovery and utilization of fire, particularly slash-and-burn agricultural practices, marked when human activities began to exert influence on nature. However, prior to 5,000 years ago, human impacts on nature were almost negligible overall.

1.1.2 Humans as Part of Nature Early human understanding of nature strictly excluded the human-nature relationship from science until the establishment of Newton' s classical mechanics in 1687. Even so, Newton still invoked God to explain the universe' s initial origin. Humboldt combined science with imagination, examining nature through the holistic perspective of the "web of life," thereby inaugurating the era of Earth science. Nevertheless, when Humboldt wrote *Cosmos* in 1845, his understanding of human impacts on nature remained superficial, consistently describing humans as merely one component of natural elements. In 1851, French physicist Foucault' s successful pendulum experiment proved Earth' s rotation, after which internal and external geological forces became important markers for the scientific construction of geology. Even then, the sources of these two geological forces came from the sun—one being gravitational force, the other thermal radiation—with human activities not included among them.

1.2 The Key to Understanding Earth Changes

Significant progress in understanding Earth changes over short timescales has primarily benefited from stratum dating techniques. First, scientists combined ice and pollen studies, ice core drilling, and palynology to conduct systematic research on Alpine glaciers. By reading trace lead layers that indicated the suspension of lead smelting during the Black Death, they confirmed that the dating method was accurate and effective, with the time period consistent with the Black Death epidemic in human society. Later, scientists used Antarctic ice cores to read about the reduction of atmospheric carbon over 100 years, which aligned with the historical period when smallpox was brought to the Americas, large numbers of Indigenous people died, and slash-and-burn agriculture declined, with former farmland briefly reverting to forest. Subsequently, scientists used dating techniques to read black carbon and fly ash from coal combustion in ice layers, finding consistency with the use of steam engines during the Industrial Revolution. Radioactive nuclides precisely recorded the year when synthetic nitrogen was invented in the Haber-Bosch fertilizer process, and even documented the rise of nuclear weapons testing in the 1950s and the shift from first-generation chlorofluorocarbon refrigerants to third-generation hydrofluorocarbon refrigerants in the 1980s, with significant declines after encountering the Montreal Protocol.

1.2.1 Stratigraphic Dating Methods In 1937, while conducting doctoral research on the Scottish shoreline, Chinese scholar Ting S. pioneered paleogeographic and paleoenvironmental studies through peat pollen analysis. The research results were included in Appendix B of the doctoral dissertation, "Pollen Analysis of Peat from Bute-Ettrick Bay." In 1954, Danish scientist Dansgaard presented at the famous first "Isotope Symposium" in Copenhagen, discussing interdisciplinary approaches to dating methods and the establishment of specialized dating laboratories. In the same year, American scholar Davis M. B. conducted interglacial pollen spectrum research in western Greenland, discovering that different ages of ice contained different vegetation pollens, which could be used to infer historical climate conditions.

1.2.2 Discovery of "Ice Memory" During the 1960s-1970s, global climate anomalies caused world food crises and severe social consequences in some regions, making climate change a cutting-edge research topic. Concurrently, in 1966, technicians from the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) discovered "ice memory" at the secret nuclear base "Camp Century" (1,390 m depth) on Greenland. Dansgaard et al. analyzed the ^{18}O isotope ratio values of 1,000 samples from the ice core, establishing the world's first long-term ice core climate record that scientifically revealed the entire process of climate change since the last glacial period. They found that Greenland only began to freeze 100,000 years ago.

1.2.3 Dating Technology and Earth Evolution Due to breakthroughs in dating techniques—such as peat spores, radioactive isotopes, paleomagnetism, stable isotopes, deep-sea drilling, and ice core retrieval—Earth scientists began studying the impacts of Earth evolution on short-term climate change. Further research from deep-sea sediments, Barbados coral reef terraces, and loess and paleosol sequences in Eastern Europe revealed that Earth is constantly changing. Thus, humans, primarily scientists, can now measure Earth evolution and its processes with high precision without uncertainty, and can even more accurately predict future major events on Earth, especially climate change and its corresponding impacts.

1.3 The New Geological Era of the "Anthropocene"

In 1983, Goody pointed out at a NASA Woods Hole symposium that "humans already have the ability to change the environment on a global scale." Later, Crutzen and Rockström collected substantial evidence and unanimously agreed that humans are no longer merely part of nature but are completely connected with the Earth system, with human activities' impacts on Earth changes surpassing other surface elements. In 2000, Crutzen formally proposed the concept of the "Anthropocene" in the International Geosphere-Biosphere Programme. In 2002, he published "Geology of Mankind" in *Nature*. In 2019, *Nature* reported that scientists voted to formally establish the "Anthropocene" as a new geological era through the 35th International Geological Congress.

2. Human Activities Changing the World Enter a Period of Great Acceleration

Humanity's use of nature to solve survival and development problems has created three major revolutions—agricultural, industrial, and technological—transforming impacts on Earth from weak to strong and gradually becoming the dominant force changing the planet. World changes have shifted from slow to accelerated and entered a period of great acceleration.

2.1 Slow Changes (I)

The first major world-changing human activity can be traced back thousands of years to the domestication of plants and animals.

2.1.1 Food Chains and the Neolithic Revolution Approximately 10,000 years ago, human society developed agriculture. In reality, no clear markers distinguish the transition to agriculture, as groups continuously changed their food supply strategies according to their circumstances, with agriculture usually being the last resort. Qiu Zhenwei et al. used direct accelerator mass spectrometry ^{14}C dating on partially carbonized rice from Hanjing, China, with calibration results suggesting that by 8,000 BCE, humans in the middle and lower reaches of the Huai River may have already begun domesticating and cultivating rice.

2.1.2 Agricultural Impacts on the World The Neolithic (agricultural) revolution changed the world on a massive scale. First, Earth' s forest coverage decreased dramatically. By 8,000 BCE, slash-and-burn agriculture began causing tremendous destruction to Eurasian forests. According to the Kyoto Protocol, since the agricultural era, global forest area has decreased by 2$×10^{7}$ km^2, causing atmospheric CO_2 concentration to increase by 10$×10^{-6}$. Second, Earth became covered by agricultural and pastoral production zones. From the perspective of civilizations with written records, by 3,500 BCE, Sumerian agricultural civilization emerged in the fertile crescent between the Tigris and Euphrates rivers. Humans cultivated wheat, barley, cucumbers, chickpeas, lentils, and other crops; invented the plow; domesticated cattle, donkeys, horses, sheep, and pigs; and learned to use oxen and horses for plowing. They also fished, hunted birds and gazelles, and completed humanity' s first revolution—the Neolithic (agricultural) revolution. To develop agriculture, humans gradually developed more productive irrigated agriculture on arid wastelands. By 3,000 BCE, Sumerians in southern Mesopotamia successfully diverted water from the Tigris and Euphrates through canals to develop agriculture and also modified soils, a process that exacerbated soil erosion.

According to historical research, although the timing of human food production' s transformation of the world varied considerably across regions, by 1,000 BCE, most of Earth' s surface had been altered by hunter-gatherers, farmers, and herders. Between 3,500 and 3,000 BCE, city-states such as Eridu, Ur, and Uruk appeared on the plains of Mesopotamia—urban states with common ancestry and territory—initiating the "urban revolution."However, they remained in long-term states of maritime trade and war without forming an integrated development pattern. In summary, between 10,000 and 6,000 years ago, humans domesticated livestock, deforested large areas for cultivation, and used land for crops, solving food shortages caused by population growth but leading to declines in Earth' s biomass, the disappearance of most megafauna populations, accelerated species extinction, and the transformation of Earth' s biota. The relationship between human activities and the natural environment gradually intensified, beginning to affect the natural world, particularly Earth' s carbon cycle and ecosystems.

2.2 Slow Changes (II)

Since the Holocene, most parts of the world have experienced centuries of cold, harsh climate. Records indicate that around 1300 CE, glaciers worldwide began extending to lower elevations, reaching their peak in the mid-17th century. The causes remain undetermined—whether from Earth' s own operation or human activities—but historical records show that during the coldest period of this Little Ice Age, half of Norway' s and Sweden' s populations died from famine.

2.2.1 The Recent Little Ice Age and Its Characteristics Based on temperature data from central England, the coldest winters and hottest summers between 1550 and 1700 occurred during this period. Between 1400 and 1814, the

Thames River in London froze 24 times, with Londoners even holding dances on the frozen river surface. During the same period, the Netherlands was also covered in ice and snow, with frozen canals becoming a feature of Dutch landscape paintings. Snow-capped mountains even appeared in Ethiopia, Africa, and ice records exist for Lake Superior, North America' s largest freshwater lake. Although European regions experienced cooling at different times, scientists cannot determine the exact start of the Little Ice Age. Notably, the global warming period that ended this Little Ice Age was roughly synchronous, occurring in the mid-to-late 19th century to early 20th century, when warmth-loving flora and fauna gradually migrated to higher latitudes and altitudes, and glaciers worldwide clearly retreated to higher elevations, altering the original Earth ice sheet morphology.

According to Chinese local chronicles—the world' s rare comprehensive encyclopedias of meteorological and climate data—Zhu Kezhen's research using relevant materials shows that China's most recent Little Ice Age began in 1500 CE (from the Jiajing era of Ming Dynasty to the Qianlong era of Qing Dynasty). Temperatures dropped by 1.3°C over 221 years (from Daoguang to Xianfeng reigns), and did not gradually rise until 1900 CE (Guangxu era), lasting 322 years.

2.2.2 Human Activities During the Little Ice Age Records from Chinese local chronicles indicate that this Little Ice Age (natural change) had enormous impacts on human society, with frequent natural disasters such as extreme cold, drought, and locust plagues, as well as social turmoil including famine refugees and peasant uprisings (Table 1). However, human impacts on nature were minimal. Some scholars argue that this Little Ice Age may be closely related to human activities. For example, Mintz and Haraway' s research suggests that when Spanish and Portuguese colonizers expanded agriculture and colonies to the Americas in 1500 CE through plantation systems, they brought smallpox, measles, and other viruses that violently decimated Indigenous populations, causing rapid population decline and a sharp reduction in slash-and-burn agriculture scale. Former farmland was reforested, and forests absorbed CO_2, releasing more oxygen. This led to a rapid decrease in global atmospheric CO_2 concentration, causing global climate cooling. Whether reduced agricultural area in South America could truly change global climate remains under investigation. In any case, the world population increased slowly during this period, from 5.0$\times10^{8}$ people in the mid-15th century to 6.0$\times10^{8}$ by the mid-17th century, then to 7.0$\times10^{8}$ by the mid-18th century, and finally to 1.0$\times10^{9}$ by the mid-19th century. Overall, human activities impacted nature, but because population growth was not rapid, impacts on nature were limited, and natural changes remained relatively slow.

2.3 Accelerated Changes (III)

After the Little Ice Age, in 1760 CE, Britain experienced the Industrial Revolution based on cotton textile technological transformation and capitalist organization of large-scale factory production. Human production activities, in addition to previous agricultural traditions' impacts on natural ecology and land use/land cover, entered the era of steam engines, coal, iron, and railways. European industrialization rapidly transformed the face of Earth' s surface.

2.3.1 Industrialization and Its Process In 1769, British inventor Arkwright established the world' s earliest modern factory—a water-powered spinning mill. After Watt improved the steam engine in 1782, human production activities completed the transition from workshop handicrafts to factory machine production. Due to steam engine improvements, humans initially used wood (forests) and later coal and other fossil energy sources to replace human, animal, and water power. The burning of wood and coal also began emitting CO_2 into the atmosphere. By 1800 CE, some small industrial zones appeared in Britain. After 1830 CE, Belgians developed new coal mining technologies, the French built the first coal-fired blast furnace for iron production, and Germans constructed the first industrial cotton mill. Because the Rhine Valley and estuary had large forest resources that could be used as steam engine fuel, industrialization rapidly spread to northern France, Belgium, and Germany. After 1850 CE, with European railway network construction, industrialization further expanded to the Netherlands, southern Scandinavia, northern Italy, eastern Austria, Catalonia, and Spain. Central and southern Britain, the Ruhr Valley, the middle Rhine, and northern Italy became Europe' s most important industrialized regions.

2.3.2 Changes in Earth' s Landscape The European industrialization process transformed Earth' s landscape. In 1800 CE, global industry was still dominated by primary sectors, with world urbanization level at only about 3%. Industrial cities were mainly concentrated in Britain, such as Glasgow, Manchester, Birmingham, Leeds, and Newcastle. By 1900 CE, Britain' s urbanization level reached 75%, making it the world' s first industrialized and urbanized country. Subsequently, American innovations in electric lighting, electric furnaces, oxygen-blown steelmaking, thermal power stations, and tungsten-chromium alloy steel materials made steel production and electricity generation rank first in the world. The introduction of automobile manufacturing technology using assembly line production propelled American urbanization. During the 121 years from 1820 to 1941, the number of U.S. cities (towns) with populations over 10,000 increased from 23 to 1,100, with urbanization level rising from 7% to 57.4%. Meanwhile, France, Belgium, Germany, the Netherlands, and other countries, along with industrialization, began competing globally for raw materials and commodity markets, promoting capitalist expansion and colonial movements beyond Europe. North America, Africa, Asia, and Latin America became primary regions for European imperialism to extract natural resources and divide commodity markets. Particularly between 1846 and 1924, Europe emigrated 5.2$\times10^{7}$ people abroad (about 10% of the total population), with most migrating to the Americas and Australia. Many famous port cities such as New York, Philadelphia, Baltimore, São Paulo, Rio de Janeiro, Buenos Aires, and Sydney experienced rapid development due to immigration.

Because of industrialization, humans not only produced food and agricultural products but also manufactured fibers (for cloth, rope, and paper), fuels (for building heating and vehicle/machine power), and recreational products (such as coffee, tea, spices, and narcotics), as well as botanical medicines. Industrialization also made it easier for humans to deforest on a massive scale and use freshwater resources without restraint, enabling the construction of global agriculture to feed the growing population, thereby causing continuous impacts on Earth' s ecology and environment. Industrialization and urbanization gradually formed a "golden triangle" economic core zone centered on London, Paris, and Berlin. Due to technological progress and monopolies, the spatial pattern of the world economy experienced unprecedented polarization. During World War II, the wartime economy on one hand destroyed economies on the front lines of Europe and Asia, while on the other hand made the American economy behind the front lines exceptionally prosperous, with the U.S. producing 32.4% of the world' s manufactured goods and holding 74.5% of world trade and gold reserves. During the war, the Soviet Union lost 2.7×10^{7} people, with countless towns, factories, and collective farms razed to the ground, yet it took only 8 years post-war to restore its economy to pre-war levels. By 1970 CE, the Soviet Union' s steel, electricity, coal, cement, and glass production had increased 5-10 times, leaping to become a superpower competing with the U.S. Post-war Japan and Germany, despite defeat, experienced several-fold or even ten-fold growth in emerging industries such as automobiles, petroleum, electricity, chemicals, and aviation.

2.4 Great Acceleration Changes (IV)

2.4.1 Human Activities Accelerating World Change

Nuclear energy utilization. The invention and use of nuclear energy represent the most sustained and impactful human activity since 1945. In 1942, the world' s first nuclear reactor was built. By 1990, 26 countries had constructed 423 nuclear power plants with a total installed capacity of 3.3×10^{8} kW. By 2020, 54 countries and regions had built 440 nuclear power plant reactors, with nuclear power installed capacity exceeding 3.9×10^{8} kW, more than 1.3 times the 1990 level. Now there are 450 nuclear power units worldwide with a total installed capacity of 4.0×10^{8} kW, more than doubling again in over 20 years. Correspondingly, nuclear radiation threats have also begun to profoundly affect the atmosphere, biosphere, oceans, rivers, soil, and even Quaternary strata.

Green Revolution. Between the 1940s and 1970s, industrialization provided agriculture with machinery and equipment, high-yield grain varieties, synthetic pesticides and fertilizers, and large-scale agricultural irrigation infrastructure, triggering the (agricultural) Green Revolution. While greatly increasing global grain production to meet food demands from the population explosion from 2.5×10^{9} to 7.6×10^{9} people, it also significantly reduced agricultural biodiversity, fundamentally changing ecological agricultural production methods since the Neolithic Revolution (the first agricultural revolution). Global food production consumes about 40% of Earth's land resources and 70% of freshwater resources. Producing chemical fertilizers annually collects about 1.2×10^{8} tons of nitrogen from the atmosphere and extracts 2.0×10^{7} tons of phosphorus from underground, leading to soil compaction, soil degradation, and eutrophication of natural water bodies in rivers, lakes, and seas, creating large-scale surface environmental pollution and even ecological disasters.

2.4.2 Great Acceleration of World Urbanization Post-war rapid industrialization and urbanization have caused humans to consume or occupy 30%-50% of terrestrial natural resources, with natural resources being consumed at an annual rate of 4%-8%. Energy consumption has increased 12-fold, and freshwater use has increased 4-fold. Simultaneously, humans emit or dump into the surface, atmosphere, oceans, and deep Earth quantities of CO_2, non-degradable organic waste, and pollutants that are 1.6×10^{4} times natural emissions. These not only further accelerate global flora and fauna extinction rates but also create unprecedented new geomorphological landscapes such as mines, pits, and floating islands on the sea surface. However, because cities provide spatial advantages related to proximity and accessibility, they promote agglomeration economies in urbanized areas. When the world urbanization level enters the range around 50%, it enters a period of great acceleration where multiplier effects and acceleration effects intertwine and accumulate (Figure 2). From 1800 to 2020, world urbanization level increased from 3% to 56.15% (Table 2). From the perspective of annual growth rate of urbanization level, from 1820 to 1941 (121 years), the world urbanization level increased from 3% to 28.20%, with an average annual growth rate of 0.144%; from 1945 to 2020 (75 years), world urbanization level reached 56.53%, with an average annual growth rate of 0.712% (Figure 4).

3. New Changes and Challenges in Earth Systems

After World War II, the modern technological revolution, which combined scientific and technological revolutions, further promoted the energy revolution of nuclear utilization and the Green (second agricultural) Revolution. Humanity broke through energy and food supply bottlenecks for survival, and industrialization and urbanization have been changing the world with great acceleration.

3.1 Climate Change Accelerating Earth Changes

Post-war human activities, with massively accelerated urbanization as the main component, have exerted strong disturbances on Earth systems, particularly as climate change accelerates Earth changes, making global warming, ocean changes, and ecosystem changes increasingly evident.

3.1.1 Obvious Global Warming On the one hand, since the Industrial Revolution (1760 CE), industrialization and urbanization have emitted large amounts of CO_2, with atmospheric CO_2 concentration increasing from 280$\times10^{-6}$ to 379.00 $mg \cdot L^{-1}$ in 2005, exceeding the highest record of the past 23,000,000 years; by 2022, it reached 415.26 $mg \cdot L^{-1}$. On the other hand, land cover and land use changes, along with special topographic and geomorphological conditions, create urban heat islands, further increasing energy demand for cooling and exacerbating CO_2 emissions. Global average surface temperature has risen by 1.10°C compared to pre-industrial levels (1850-1900 average). In China, based on 110 years of observational data, the average annual surface temperature has risen by 0.46°C, with greater warming in western than eastern regions, and significantly higher warming rates in northern than southern regions, with the largest warming rate in the Tibetan Plateau region. According to data from 1930s-1990s Chinese average temperature spatiotemporal change research, near-surface temperatures in 16 typical mega-cities increased by 0.02°C annually. Based on 140 years of temperature data from Shanghai, the average annual temperature increased by 1.22°C, with an average warming rate of 0.0072°C $\cdot a^{-1}$ before the 1950s-1960s, 0.0163°C $\cdot a^{-1}$ during the 1950s-1960s, -0.0430°C $\cdot a^{-1}$ during the 1970s-1990s, and 0.0317°C $\cdot a^{-1}$ after the 1990s.

3.1.2 Accelerated Sea Level Rise Global warming increases ocean surface temperatures and volume, causing sea level rise. Over the past 100 years, global sea level rise has been about 1.0-1.5 $mm \cdot a^{-1}$, with Japanese coastal sea level rising at 2.0 $mm \cdot a^{-1}$ and China' s South China Sea rising at 3.0 $mm \cdot a^{-1}$. China' s coastal sea level shows an accelerating trend, with an average rise of 2.0 $mm \cdot a^{-1}$ over 100 years. The Pearl River Delta sea level has risen by 20 cm in the past 100 years, with an average rise of 3.5 $mm \cdot a^{-1}$. On the one hand, marine ecosystems experience increased marine algae and massive accumulations of decaying matter due to rising seawater temperatures. Additionally, as atmospheric CO_2 is absorbed by seawater, it changes seawater hydrogen ion and carbonate ion concentrations, directly causing ocean acidification. Compared to pre-industrial times, Earth' s surface seawater pH has decreased by 0.1. Ocean acidification promotes dissolution of carbon deposits on the ocean floor, interrupting the carbon source that marine organisms use to secrete for building their skeletons, causing 50% of Earth' s coral reefs to bleach and 70% of coral reef species to face extinction. Organisms dependent on coral reefs have also declined dramatically, threatening fisheries and putting corals, plankton, and crustaceans on the path to extinction, causing ocean dead zones to continuously expand. On the other hand, urbanization processes also cause massive impacts on terrestrial ecosystems.

3.1.3 Accelerated Ecosystem Changes Urbanization processes are causing "great acceleration" extinctions of Earth species at rates exceeding 3 times historical averages. Due to urban construction, Changzhou City alone filled in half of its ponds and small rivers, causing 50 species to disappear. Industrialization and urbanization discharge 4.5$\times10^{10}$ tons of sewage into rivers, lakes, and seas annually—more than 9.9$\times10^{9}$ times the annual runoff of the world' s four largest rivers (Amazon, Congo, Yangtze, and Orinoco) combined. According to a UNEP research report, over 70% of world rivers are polluted to varying degrees. Due to river pollution, soil, groundwater, and air pollution follow, with at least 50% of urban populations and 30% of rural populations in developing countries lacking safe drinking water year-round. Meanwhile, due to global industrialization and urbanization, Earth consumes about 30% of freshwater from rivers, lakes, and aquifers annually, with about 25% of river water being used up before reaching the ocean. Because manufacturing consumes large amounts of natural resources and increases environmental pollution, since 1950, Earth has annually emitted 1.6$\times10^{9}$ tons of SO_2—1.6$\times10^{4}$ times natural emissions. Traditional ecological agriculture has also been fundamentally changed by industrialization and urban agriculture intensification, with its emissions accounting for 33% of global total greenhouse gas emissions. Scientists believe that increased atmospheric CO_2 density and heat absorption content is the main cause of global warming.

3.2 Urbanization Creating Survival Crises

Since World War II, massively accelerated urbanization has brought unprecedented urban ecological, vulnerability, resource-environment, and public health problems to human society, posing enormous threats and challenges to human survival and development.

3.2.1 Urbanization Driving Resource and Environmental Problems

The massively accelerated urbanization process has consumed over 50% of Earth' s natural resources. Since 1978, China' s urbanization alone has consumed 40% of global natural resource manufactured goods (Table 4), using 4.3$\times10^{9}$ tons of cement—more than the entire 20th-century U.S. consumption. Due to global industrialization and urbanization, every 100 years, 6.6$\times10^{4}$ km^2 of land becomes desert, with about 2$\times10^{7}$ km^2 of land losing economic value annually. In temperate continental shelves, 70% of marine fisheries have been overfished, eliminating more than 90% of marine life. However, the number of poultry and livestock raised by humans reaches 2.5$\times10^{\{10\},withlivestockfarmingaccountingfor70}$ {2}$ annually. Acid rain causes toxic metal migration, seriously endangering forests and wildlife.

3.2.2 Increasing Negative Effects in Urbanized Areas When cities develop to a certain stage, rising land prices increase urban infrastructure construction costs and operational expenses, causing urban agglomeration diseconomies and even negative externalities for urban development. Since 2000, China' s urbanization has grown rapidly (Figure 4), with the Yangtze River Delta urbanizing fastest, adding 2,823 km^2 of various construction land, with the Suzhou-Wuxi-Changzhou area adding 540 km^2 at an average annual growth of 257 km^2. Urban and surrounding natural water body areas have decreased, weakening urban flood storage capacity and causing severe urban flooding in 1991. Since the 1960s, the Yangtze River Delta has formed a huge groundwater depression cone (Table 5) covering over 8,000 km^2 due to excessive groundwater extraction, with Shanghai' s maximum subsidence reaching 2.63 m. Due to land subsidence affecting flood control and urban safety disaster prevention, Shanghai has spent an additional $2.9×10^{9} in recent 20 years, also causing soil degradation, biodiversity loss, and serious ecological crises.

3.2.3 Vulnerability Issues in Metropolitan Areas Super metropolitan areas, due to rapid expansion, face greater vulnerability when encountering natural or human-made disasters—from earthquakes, floods, typhoons, and storm surges to production accidents, infectious diseases, or wars. Once a major city experiences a sudden event, it may fall into urban chaos or even shock within a short time. For example, in 2014, Shanghai' s New Year' s Eve activities on the Bund caused a stampede resulting in 36 deaths and 49 injuries. In 2021, Zhengzhou' s "7·20" extreme rainstorm caused urban flooding that forced 1.0×10^{6} people to evacuate, paralyzed urban traffic locally, and interrupted power supply and communication infrastructure.

Climate change causes changes in rainfall and humidity in metropolitan areas and large cities, while rapid urban expansion leads to heat island effects and ecological niche changes, awakening and expanding pathogens and viruses previously confined and isolated in wild environments (especially in the cryosphere), changing insect and animal habits and biological environmental adaptability, and even altering habitats for bacteria, animals, and the biological world, providing conditions for novel coronavirus transmission and becoming a major trigger or transmission node for international public health emergencies. In recent years, with rapid growth of global mega-cities and increased population mobility, previously controlled diseases such as cholera and plague have re-emerged, while new infectious diseases have appeared, including AIDS, Ebola virus, Legionnaires' disease, avian influenza, and COVID-19. Each year, 5.0×10^{6} people worldwide die from various infectious diseases, with over 50% of African deaths originating from infectious diseases. Since the WHO established the "International Public Health Emergency" mechanism in 2007, there have been 7 instances. The 2020 COVID-19 pandemic quickly made cities like Wuhan, New York, London, Milan, Madrid, and Tokyo disaster-stricken areas, with Shenzhen, Xi' an, Shanghai, and Beijing' s economies and societies also severely impacted.

3.3 Systemic Crises

3.3.1 Earth Systemic Crisis Against the backdrop of highly developed human society and world economic systems, with continuous growth in world population and GDP, if greenhouse gas emissions and Earth' s surface temperature maintain current levels, global change indicators such as Arctic sea ice melting, Amazon rainforest precipitation changes, Australian coral reef bleach-ing, Siberian permafrost melting, ocean acidification, and coastal nitrogen will change dramatically, causing systemic crises in Earth' s natural systems, ecosystems, freshwater resources, global food supply systems, coastal urbanization infrastructure, human health, and property safety. Natural-social systems construct a global change and Earth evolution causal network with cities as hubs, while human activities highly integrated with artificial intelligence, the internet, and ecosystems become the third and most active, dominant new force of Earth evolution and movement. With population growth, urban external impacts increase exponentially, especially as large cities, mega-cities, metropolitan areas, and urban agglomerations exhibit their own heterogeneity and diversity, leaving new problems and major challenges for Earth science while also adding new momentum and space for its development.

3.3.2 Ocean Systemic Crisis According to the IPCC assessment report, if existing economic and social life patterns remain unchanged, global surface temperature will rise by 1.1-6.4°C in the next 50-100 years, reaching the highest temperature since Earth formed 4.5×10^{9} years ago. If temperature rises further, it will cause the Atlantic meridional overturning circulation to weaken or even collapse, bringing severe impacts to weather and climate environments in the Northern Hemisphere, especially Europe and North America, with Europe facing significant cooling and Earth entering another "Little Ice Age" caused by human activities. Based on historical data, for every 1°C rise in Earth' s average temperature, sea level may rise by 10-20 m. According to Swedish Academy scientist Hekstra' s estimates, 1.6×10^{9} people and world-famous metropolises such as London, New York, Tokyo, Shanghai, and Hong Kong, as well as medium and large cities with populations exceeding 1.0×10^{6}, are located in estuaries and coastal zones. Dense populations, rapidly developing urban economies, and complex ecological environmental systems make estuary cities the most sensitive areas to climate change. In the next 100 years, global sea level will rise by 0.42 m, with the Nile Delta, Ganges Delta, Yangtze River Delta, Yellow River Delta, and Pearl River Delta all showing rising trends.

Yangtze River Delta. By 2050, sea level will rise by 0.25-0.30 m, with Shanghai' s sea level rising by 0.27-0.61 m, and the northern Jiangsu plain area rising by 0.45 m. Even Tianjin and Hebei Province coasts will face threats of seawater inundation.

Pearl River Delta. By 2030, sea level will rise by 0.10 m, with more than half of low plain ground below sea level; by 2050, sea level will rise by 0.20 m, submerging all low plains and some high sand and high embankment areas; by 2100, sea level will rise by 0.50 m, with the northern Pearl River Delta rising by 0.25-0.30 m.

3.3.3 Economic Systemic Crisis For the world' s most powerful mega-regions, climate change may cause catastrophic blows. Taking China as an example, two major economic centers will be affected.

4. New Characteristics and Fields of Earth Science

In Earth's history, major events such as supercontinent aggregation and snowball Earth events, and super mantle plumes and biological extinctions have occurred. Although these also took geological time units, they were eventually lost to time. However, when industrialization, urbanization, and modern technological revolutions become the dominant forces promoting and driving Earth changes, the lithosphere, atmosphere, hydrosphere, soil sphere, cryosphere, and biosphere are all affected. Earth system operation has also surpassed the two forces that have existed for hundreds of millions or even billions of years—external solar energy and internal Earth energy. Greatly accelerated urbanization is becoming the third and most active, dominant new force. With population growth, urban external impacts increase exponentially, especially as large cities, mega-cities, metropolitan areas, and urban agglomerations exhibit their own heterogeneity and diversity, leaving new problems and major challenges for Earth science while also adding new momentum and space for its development.

4.1 New Characteristics of Earth Science

From the perspective of natural evolution and human development history, Earth' s surface system predecessor was the lithosphere, formed about 4.5×10^{9} years ago. About 4.2×10^{9} years ago, the hydrosphere formed, and about 3.8×10^{9} years ago, life differentiated from Earth' s inorganic world. Since the emergence of ancient Greek geography 3,000 years ago, the space that humans have focused on and studied in understanding the surrounding world has included the land surface, lithosphere, atmosphere, hydrosphere, biosphere, and their interacting interface changes.

In 1883, Dokuchaev recognized that "soil is a historical natural body formed by the interaction of five factors: parent material, climate, organisms, topography, and time," providing scientific demonstration of the "cold, temperate, subtropical, and equatorial zones" described in ancient Greek geography, publishing *On the Doctrine of Natural Zones: Horizontal and Vertical Soil Zones.* In 1926, Vernadsky proposed the biosphere concept based on Dokuchaev' s soil zones: the area between the bottom of the atmosphere, most of the hydrosphere, and the surface of the lithosphere where Earth experiences and is influenced by life activities. In the Earth sphere system, the largest ecosystem was constructed for biogeochemical force research. Later, Vernadsky further divided the biosphere into the natural sphere, biosphere, and anthroposphere. He also believed that for Earth' s functions, dynamics, and evolution, the biosphere is largely creative rather than destructive. The anthroposphere emerges when human capabilities grow sufficiently large to have destructive effects on Earth systems. Before 10,000 years ago, human society created the Neolithic (agricultural) revolution; 6,000 years ago, the urban revolution emerged; 200 years ago, Britain produced the Industrial Revolution; and after World War II (less than 100 years), the modern technological revolution exploded. Human intelligence and corresponding activities have generated the ability to change Earth, and this ability grows daily, perhaps even astonishing and overwhelming to humans themselves. Earth science will thus transition from pure natural sphere research to composite natural sphere-anthroposphere research.

In recent years, the "Planetary Boundaries" theory has attracted Earth scientists' attention. The theory posits that Earth systems are becoming increasingly sensitive to thresholds. Once certain thresholds or tipping points are exceeded, catastrophic or even destructive mutations may occur. As long as thresholds are not breached, human society will still have space for socio-economic development and human living space. Since the Planetary Boundaries theory was proposed, researchers have increasingly recognized that the scale of human social systems is constrained by Earth' s natural systems. As scholars in scientific and social fields continuously improve their understanding of the nine elements of the Planetary Boundaries theory, the relevant Earth science research scope will gradually shift from single disciplines in stratified natural sciences to integrated research viewing Earth as a single, unified anthroposphere-natural sphere system. By adding a series of socio-economic variables, planetary boundaries can be expanded for integrated research within socio-economic systems in the anthroposphere.

4.2 New Fields of Earth Science

To address the reality of Earth system changes and human activities as the third and increasingly dominant force, several important research directions are becoming key focus areas for Earth science (Figure 5).

4.2.1 Habitable Planet Research Before 3.8×10^{9} years ago, Venus, Earth, and Mars in the solar system' s habitable zone as defined by astronomy had no life. Through internal dynamic processes, deep Earth surface and space material cycles, Earth developed habitability distinct from other planets. In the recent 200 years, due to the Industrial Revolution, modern technological revolution, and rapid urbanization, human activities have intensified Earth' s physical, chemical, ecological, and environmental changes, with large fluctuations in the carbon cycle, ocean acidification, and ocean carbonate levels 50 times higher than in the atmosphere, accelerating marine population extinction. As Gao Yang et al. recently integrated analysis of global land-air carbon transport and carbon budget changes, similar research can open new ideas for human habitability studies on Earth and even extraterrestrial planets.

4.2.2 Anthropocene Research As a new geological epoch, the Anthropocene requires determining specific geological markers or "golden spikes" — Global Boundary Stratotype Section and Points. Which human activities most clearly reflect Earth changes related to the Anthropocene' s start? The selection of "golden spikes" is still under research. In 2013, anthropologist Palsson pointed out that the Anthropocene epoch signifies a fundamental change: conceptually and behaviorally, humans have become alert to their responsibility for the fragile Earth. Therefore, Anthropocene research not only studies the relationship between human activities and Earth changes but also needs to study new architectures originating from human activities and connected with multiple global assemblages.

4.2.3 Anthroposphere Geography The anthroposphere is the foundation of geography' s formation and development, and Earth science should prioritize the development of anthroposphere geography. First, define the anthroposphere' s spatial-temporal composition. While human impacts on Earth are seen as the Anthropocene' s starting point, truly understanding these impacts requires establishing spatial-temporal relationships between human activities and Earth—a huge and multi-dimensional system requiring research on different driving forces across multiple periods: fire discovery and use in primitive society, the Neolithic (agricultural) revolution, the urban revolution, the Industrial Revolution, and the modern technological revolution. Second, reconstruct new human-environment research frameworks. From Humboldt' s *The Natural World* to Marsh' s *Man and Nature*, Kropotkin' s *On the Law of Mutual Aid* in the 1970s-1980s, and Reclus' s *The Feeling for Nature in Modern Society*, research on human-environment relationships and human impacts on natural changes has always been geography' s theme. However, although Marsh 引用 d Stoppani' s concept of "humans as infinite and powerful" to strengthen the impact of human activities, 20th-century geography largely defined humans and environment as two different systems. Contemporary human-environment relationship research requires geographers to face challenges from human society and global change, establishing new geographical research methods. Third, topological innovation research. Since the 1970s, biophysics and social sciences have 各自引用 d topology for disaster inflection point research. Geographers' research on lakes, coral reefs, oceans, forests, and arid lands also shows that smooth gradients may be interrupted by sudden dramatic transitions. Global change also has similar mutations; once thresholds are breached, Earth may irreversibly lock into continuous degradation states, with these states showing more dramatic spatial and temporal jumps. Promoting human-environment relationship topology research and humanizing topography' s research subjects may become effective methods for describing Anthropocene spatial evolution processes.

4.2.4 Cryosphere Science Research Due to 200 years of industrialization and 100 years of urbanization, human activities have caused climate change, global warming, and sea level rise, profoundly affecting Earth' s cryosphere. As the cryosphere lies between human habitation zones and uninhabitable zones, with 52%-55% of land covered by the cryosphere (Antarctic ice sheet, Greenland ice sheet, and mountain glaciers accounting for 10%, permafrost regions 1.3%-30.6%, and Northern Hemisphere seasonal frozen soil (including permafrost active layers) 9%-12%), cryosphere science has greater scientific value for studying human-environment relationships affected by climate change.

4.2.5 Hydrosphere-Anthroposphere Interface Research Due to high-speed population and economic growth and many unsustainable human activities, global freshwater resources are becoming increasingly scarce. High-frequency, high-intensity climate change also causes precipitation, drought, and secondary disasters that seriously threaten water resource security and human production and life. Under the background of human activities dominating Earth systems, water resources face huge challenges on the one hand, and increasing attention must be paid to human disturbances and responses in hydrological systems. Parameterization schemes reflecting human water use activities need to be coupled with hydrological models for human activity-based water cycle simulation research. Meanwhile, due to climate change, water resources are core elements for maintaining ecosystem integrity and ensuring social life. Drought and flood disasters cause major impacts on human society, and regional water resource disputes and conflicts will continuously intensify, promoting traditional terrestrial hydrology in Earth science to shift toward human-hydrosphere interface steady-state conversion, especially research with human activities as driving factors, which will become a new Earth science research field.

4.2.6 Earth System Dynamics Research Since human activities have become the third major force driving Earth system change after solar energy and Earth' s internal energy, Earth systems have become complex large systems coupling natural and social systems. Research methods are needed that not only use stratigraphic chronologies obtained by geologists to describe and explain Earth space but also apply biological evolution chronologies obtained by biologists through the biosphere and historical chronologies formed by social scientists studying human development history to compose diversified Anthropocene chronologies. Earth system dynamics research based on three-dimensional "chronologies" is both a new demand for Earth science development in the new era and will make Earth science more systematic and scientific.

4.2.7 Urbanization Research and Urban Geography Urbanization, a non-natural body created by humans over 6,000 years, has become the main contemporary human activity through the Industrial Revolution and modern technological revolution, continuously and acceleratively reshaping the natural environment, human society, and the entire Earth in an apparently infinite yet destructive manner. Mega-cities, urban agglomerations, and mega-regions (massive urbanized areas), as engines and force sources of Anthropocene Earth system changes, have entered a period of digital and networked social transformation and massive accelerated growth. Responding to climate change and economic globalization, in-depth research on urbanization and its interactions with Earth systems offers broad development prospects for urban geography.

4.2.8 Geoethics and Semiotics When problems arise in human-environment relationships, the ways and intensity of human impacts on nature are often influenced by ethics. Geoethics and semiotics emphasize human adaptation to and modification of nature, elevating era research most directly related to human activities from social cognition to academic research. Specifically, geoethics and semiotics construct the relationship between humans or society and nature or Earth, 致力于 ing dialogue between humanities and natural sciences to respond to Earth diseases in the Anthropocene.

4.2.9 EarthMAP Integration Earth science is also a discipline highly dependent on observation data. EarthMAP, based on different principles of multiple navigation, positioning, and timing information sources, is the most important characteristic for multi-source information collection, comprehensive analysis, and utilization. Machine learning and artificial intelligence technologies have been successfully used in volcanic and earthquake early warning monitoring, weather forecasting, water and soil resource development and utilization, energy development, and territorial spatial planning. Using rich Earth and biological datasets, sensor technology advances, improved integrated modeling, machine learning, and high-performance computing (including cloud computing) to observe, understand, and predict Earth changes across spatiotemporal scales in real-time and predictive ways. Without maps, there would be no Earth science. EarthMAP will undoubtedly provide a platform for research and results display for Earth science in the new era, also allowing Earth science to move toward society and decision-making applications.

5. Mission of Earth Science in the New Era

Since the Industrial Revolution, industrialization-driven urbanization has become the dominant factor in climate change, bringing tremendous changes to nature and human society. Due to its agglomeration effects, it is now changing Earth with great acceleration, and Earth' s complex natural and human social systems are already in increasingly severe crises and threats. Climate change and urbanization, on the one hand, bring a series of problems related to Earth systems, resources and environment, urban development, public health, and social vulnerability, and on the other hand, by viewing Earth' s interior, surface, and near-space as a unified whole and exploring climate and hydrological cycle processes, ecosystems and biogeochemical cycle processes, solid Earth processes, and human impacts on Earth, they create new demands and inject new momentum into Earth science development, ushering Earth science into a new Anthropocene era. When industrialization, urbanization, and modern technological revolution human activities become the dominant forces promoting and driving Earth changes, both humans and environment and humans and Earth are in symbiotic relationships. Developing the economy can eliminate poverty and achieve social equity, which are preconditions, making social and environmental justice new issues facing Earth science. To stop and reverse climate change, global warming, and global environmental change, Earth science needs transformation and innovation, conducting scientific research across all spheres affected by human activities—lithosphere, atmosphere, hydrosphere, soil sphere, cryosphere, biosphere, and anthroposphere—at multiple scales, strengthening Earth' s systematic management, and building new relationships between science and society to address climate and energy challenges. Earth science has already shown new characteristics of shifting from strata to spheres and from pure natural systems to human-Earth complex large systems. Some new directions are becoming new research focus areas for Earth science, and research priorities will shift from Earth resource extraction to broad planetary habitability, Anthropocene and its research, anthroposphere geography, cryosphere science, hydrosphere-anthroposphere interface, Earth system dynamics, urbanization and urban geography, geoethics and semiotics, and EarthMAP integration. These will become new growth points for Earth science development. Geography, spanning natural and human sciences, can help humanity accurately understand human-environment relationships through the integration of natural and human scientific knowledge, and will undoubtedly become the most promising discipline in Earth science, with human geography in particular playing a greater key role in the new era of Earth science.

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Note: Figure translations are in progress. See original paper for figures.