Carbon Budget Verification for Climate Change Mitigation and Related Issues: Postprint

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Abstract

Since the Industrial Revolution, human activities have caused an increase in the concentration of atmospheric greenhouse gases such as CO2, thereby triggering global warming. The global change arising from this has become a common goal for humanity in addressing climate change. Curbing the rapid rise in global temperature has become an issue of international common concern in recent decades, and also constitutes the negotiation theme regarding emission reduction contributions of various countries in the international community. With respect to the scientific and technological policy measures required for international negotiations and emission reductions, China, as a major developing country and the world' s second-largest economy, plays a significant role and exerts substantial influence. Our country' s rapid development in recent years has made evident contributions to world economic development and human progress. Similarly, due to disparities in development scale, speed, and technological advancement, China has become a major emitter of greenhouse gases, a situation that will be difficult to change substantively for a long period to come. From the perspective of requirements for international climate change negotiations and the need for sustainable and green pathways in our country' s economic and social development, it is urgently necessary for our scientific and technological community to provide scientific and quantitative answers to the following major scientific, technological, and related policy issues.

Full Text

Preamble

Strategic Priority Research Programs (Category A) of the Chinese Academy of Sciences, ChinaXiv Partner Journal: Carbon Budget Certification and Related Issues for Climate Change Response

1. Project Background and Significance

Human activities since the Industrial Revolution have increased atmospheric concentrations of greenhouse gases such as CO , causing global warming. This global change has become a common objective for humanity in addressing climate change, and curbing rapid temperature rise has emerged as a globally significant issue of international concern in recent decades, forming the basis for negotiations on national emission reduction contributions. In the context of international negotiations and the scientific, technical, and policy measures required for emissions reductions, China—as a major developing country and the world' s second-largest economy—plays a significant role and exerts considerable influence. China' s rapid development in recent years has made undeniable contributions to global economic development and human progress. However, due to the scale, speed, and technological gaps in its development, China has become a major greenhouse gas emitter, a situation that will be difficult to fundamentally change for a long time to come.

From the perspectives of international negotiation requirements for climate change response and the needs of sustainable, green pathways for China' s economic and social development, it is urgently necessary for China' s scientific community to provide scientific and quantitative answers to several major scientific and policy questions:

(1) What are China' s greenhouse gas emissions? A comprehensive understanding of China' s actual emission intensity and volume is essential. This represents one of the core requirements for China to gain stronger discourse power in international negotiations. To address this, comprehensive sampling and statistical analysis of all major energy sources and human activities generating greenhouse gases must be conducted, with quantitative answers provided using internationally advanced technologies. Since coal is China' s primary energy source, special attention is required.

(2) What is the carbon sequestration potential and rate of China' s terrestrial ecosystems? Using internationally advanced and standardized methods, representative measurements and analyses must be conducted across all types of ecosystems nationwide. China has established six major ecological restoration projects over recent decades, which have made significant contributions to carbon sequestration that must be quantitatively estimated. New technology trials should be conducted based on local conditions to provide advanced solutions for green development.

(3) How can "MRV" (measurable, reportable, and verifiable) greenhouse gas emissions reduction be achieved? An integrated monitoring system for greenhouse gas distribution and variation must be established, incorporating satellite monitoring, ground-based measurements and verification, and multiple advanced methods. This will enable China to become an equal and active participant in MRV issues.

(4) Does the 2°C warming target correspond to a greenhouse gas concentration of 450 ppm CO equivalent? The correspondence between 2°C warming and 450 ppm CO equivalent concentration was a consensus reached by international political and scientific communities during the 2009 Copenhagen negotiations. Chinese scientists recognized that this correspondence was inadequate and should be improved through more advanced models. More reliable quantitative knowledge of China' s atmospheric temperature changes over the past century to millennia must be obtained. China' s substantial increase in aerosol content is also an important factor affecting climate change. Through multiple scientific approaches, better projections of the relationship between warming and greenhouse gas concentrations should be made.

(5) What were China' s ecological environments like during historical warm periods, and how did humans adapt? Earth experienced a warm period 6,000–8,000 years ago with temperatures similar to current conditions. Understanding how China' s ecological environment and humans adapted and developed during this Holocene Warm Period and previous ice ages can provide valuable insights for current climate change challenges.

(6) What are the green development strategies and policies for climate change response? Based on this special program' s research and combined with domestic and international developments, policy recommendations for national climate change response will be proposed to continuously leverage the program' s research achievements.

To address these national strategic objectives, the Chinese Academy of Sciences established the Strategic Priority Research Program "Carbon Budget Certification and Related Issues for Climate Change Response," organizing multidisciplinary experts from within and outside the Academy to conduct five years of intensive research through five task groups comprising 15 projects. Over the five-year period, 98 research units participated, with more than 4,000 scientific and technical personnel engaged in the work. Through dedicated efforts and collaboration, participants have essentially achieved the program' s scientific objectives, producing scientific results for national climate change negotiations, providing advanced technical systems, methodological foundations, and standard specifications for national green development, and offering policy recommendations that keep pace with domestic and international developments. The program participated in side events and exhibitions at the 2015 Paris Climate Conference, playing a comprehensive role in providing scientific and strategic support for the nation. The scientific platforms and databases constructed by the program will continue to serve major national needs, while the multidisciplinary collaborative organization formed through program implementation has created a scientific talent team for the Chinese Academy of Sciences that addresses major national strategic needs while remaining at the forefront of international science and technology.

2. Major Progress

2.1 Quantitative Estimation of Energy Consumption and Cement Production Emissions

Based on authoritative Chinese statistical data, the program measured carbon loss quantities for various energy types through investigation and data collection, thereby obtaining consumption data for each energy type. Through extensive statistical analysis, the program determined carbon content per unit fuel and calorific values for different energy types. Sampling data collection and analysis were conducted for major industries and enterprises using primary energy sources in China, yielding carbon oxidation factors for different industries. This enabled calculation of energy consumption types, quantities, and actual CO emissions for different industries, and subsequently the total CO emissions for different energy types in China. A comprehensive database and visualization system for China' s energy utilization and cement production was constructed.

2.2 Quantitative Assessment of Carbon Sequestration Capacity in China' s Terrestrial Ecosystems

(1) Current status, rate, mechanisms, and potential of carbon sequestration in China' s terrestrial ecosystems. The program developed field investigation technical specifications and data integration protocols for ecosystem carbon budget research, leading and promoting related research in China. A Chinese land cover classification system was developed that conforms to the Intergovernmental Panel on Climate Change (IPCC) carbon accounting system. Using satellite data and ground survey validation, a land cover system was established with average accuracies of 94% for first-level classification and 86% for second-level classification, both reaching world-leading levels. The world' s first national-scale terrestrial ecosystem carbon inventory system was constructed, which will play important roles in multiple fields.

A comprehensive database of China' s terrestrial ecosystem carbon budget was built, acquiring data on carbon storage and community structure across different components from more than 16,000 sample plots in forest, shrubland, grassland, and farmland ecosystems, filling gaps in this database. This laid an important foundation for achieving measurability, reportability, and verifiability.

(2) Investigation, measurement, and evaluation of carbon sequestration by major national ecological engineering projects. China has implemented six major ecological engineering projects. Based on the characteristics of each project, corresponding evaluation methods for carbon sequestration were established. Results show that the total area of China' s six major ecological engineering projects is approximately 1.82 million km², accounting for about 19% of the country' s land area. The increased carbon sequestration after project implementation is approximately 4.57–5.24 PgC, highlighting the important role of China' s major ecological engineering measures in enhancing ecosystem carbon sinks.

(3) Technology systems and demonstration trials for carbon sequestration enhancement in typical Chinese regions. Four types of regions were selected nationwide to reveal the main causes of ecosystem degradation such as overgrazing and excessive logging. Different ecological improvement and carbon sequestration enhancement technical approaches and measures were proposed for different regions based on their specific degradation processes and degrees, providing a scientific and technological demonstration foundation for green development.

2.3 Enhanced Climate Change Sensitivity Research and New Results on Warming-GHG Concentration Relationships

(1) Establishment of homogenized centennial temperature series for China and new understanding of warming. Centennial-scale instrumental temperature data were collected and compiled with strict quality control, establishing monthly temperature value series from 1909–2009 for 18 stations. A new set of centennial temperature series was ultimately obtained. Comparison of the newly established centennial temperature anomaly series with long-term trends from the Climate Research Unit (CRU) at the University of East Anglia for eastern and entire China shows that several data series almost overlap in recent decades. The homogenized temperature series reveals a warming rate of 1.52°C (100 yr) [1], which is faster than the global average warming of 0.89°C from 1901–2012 reported in the IPCC Fifth Assessment Report, indicating that China has experienced relatively large impacts from anthropogenic global warming in recent centuries.

(2) New understanding of national-scale, long-term, systematic concentration and optical parameter observations and the importance of Chinese aerosols. The IPCC Fifth Assessment Report (AR5) noted that aerosol climate effects remain the most uncertain component among all factors, with Chinese aerosols being particularly important in climate change. To address this, the Chinese Academy of Sciences established an aerosol ground concentration observation network and an aerosol-cloud-radiation observation network, systematically conducting observational research on aerosols and their climate effects in China [Figure 1: see original paper]. Three-year data on mass concentrations of major aerosol components in nine size segments, spatiotemporal characteristics of aerosol gaseous precursors, and spatiotemporal distributions of aerosol optical properties were obtained, providing fundamental parameters for regional and global climate model simulations with scientific advancement both nationally and internationally. Based on observational data, it has been confirmed that aerosol-climate models adopted by IPCC AR5 generally underestimate aerosol concentration and optical depth in China, presenting new challenges for aerosol climate effect simulation research internationally.

(3) Development and improvement of the Chinese Academy of Sciences Climate System Model (CAS-CSM). Targeting several key physical processes that significantly affect climate model simulation uncertainties, corre-

sponding parameterization schemes were developed and improved. Through coupling integration, CAS-CSM was enhanced and perfected. A new cloud-aerosol-radiation ensemble system in the atmospheric circulation model was developed. The global vegetation dynamics model CAS-DGVM was developed, improving simulation of vegetation ecological patterns and structures. CAS-DGVM can well simulate the global distribution patterns of major natural vegetation types under current climate conditions while effectively characterizing the mapping relationship between climate and vegetation distribution.

(4) Estimation of CO equivalent concentration corresponding to 2°C warming based on transient climate simulations. The IPCC prepared emission inventories (Representative Concentration Pathways, RCPs) for AR5 chemical species simulations. Multiple RCPs represent different assumptions about future socioeconomic development. The study obtained CO equivalent concentrations and emergence times corresponding to 2°C warming under future emission scenarios (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5). Based on simulation results from multiple global climate models, the CO equivalent concentrations corresponding to 2°C warming under RCP4.5, 6.0, and 8.5 scenarios are 542, 560, and 563 ppm, respectively, all significantly higher than 450 ppm. The study also indicates that current climate models still have substantial uncertainties in projecting the emergence time of 2°C warming and its corresponding CO equivalent concentration due to factors such as water vapor and cloud effects.

2.4 New Understanding of Holocene Warm Period Environmental Patterns and Human Adaptation Processes in China

(1) Environmental patterns and implications of the Holocene Warm Period. Through research on multiple high-precision geological and biological records, it was revealed that warming will benefit forest area expansion in China and increase C4 plant abundance in northern regions, leading to increased precipitation in monsoon regions and amplified seasonal temperature variations, as well as increased terrestrial ecosystem carbon storage. During the Holocene Warm Period, deserts east of the Helan Mountains were largely stabilized, and terrestrial ecosystem carbon storage was 10 Pg C greater than at present.

(2) Important progress in research on human adaptation to climate change. Project teams conducted excavations and sampling at over 600 key archaeological sites, obtaining important samples of prehistoric humans, animals, and plants. Discoveries include the earliest modern human fossils in East Asia and evidence of continuous evolution of Paleolithic culture, revealing that agricultural technology facilitated large-scale settlement of prehistoric humans on the Tibetan Plateau. These research achievements have generated major academic and social impact, such as "Ancient DNA Decrypting Modern Human Origins" being selected as one of *Nature* magazine' s "Top 10 Scientific Events of 2014," and "Transitional Fossil Evidence of Early Modern Humans in China" being selected among the "Top 10 Scientific Advances in China" for 2015.

2.5 New Achievements in Green Development Research Providing Important Support and Policy Recommendations for International Negotiations and National Development

Through policy-oriented research, the program proposed systematic solutions for green and low-carbon development from the perspectives of "objectives, policies, management, and support," achieving a series of influential results. Carbon peak research was conducted under the background of ecological civilization construction.

Methodologically, quantitative analysis models were developed, including the PIC model jointly developed with the United States and multiple independently constructed models. Scientific, systematic, and representative national household carbon emission sampling survey samples were obtained, and a database was constructed. A carbon footprint inventory database for China' s basic products was established.

The program submitted nearly 40 consultation reports, including 3 with instructions from national leaders, 9 adopted by the General Office of the Communist Party of China/General Office of the State Council, and 5 as National People' s Congress representative proposals. Research results supported decision-making and international negotiations on climate change response. Carbon emission peak research was presented at the "U.S.-China Climate Negotiation Expert Dialogue," supporting the formulation of China' s 2030 carbon emission targets and the signing of the U.S.-China Climate Change Joint Statement. Research results also supported the compilation of climate change response and low-carbon development sections in the 13th Five-Year Plan.

3. Major Impact

3.1 Emission Inventory Research and Estimation Received High Attention from NDRC and International Recognition

The program' s research on Chinese carbon emission parameters has been highly recognized internationally. It was found that China' s carbon emissions had been overestimated by 10%–15% for a long period by major foreign research institutions. In collaboration with 24 institutions including Harvard University, CDIAC, EDGAR, and Tsinghua University, a paper was published in *Nature* and submitted to the State Council General Office. Major domestic and international media including CNN, *Science*, *People' s Daily*, and *Guangming Daily* have generally recognized the research results. The re-estimated Chinese carbon emissions are 10.6 billion tons of CO less than previously estimated for the period 2000–2013, increasing the emission reduction space by 25%–70%. At the request of the National Development and Reform Commission (NDRC), program research results were interfaced with the NDRC Climate Strategy Center to provide data for the Third National Communication. The program participated in the compilation of the national emission inventory, adopting the program' s new carbon oxidation factor calculation method and providing newly surveyed data.

3.2 Chinese Temperature Reconstruction Results Incorporated into Third National Climate Change Assessment Report

The Third National Climate Change Assessment Report, particularly regarding the division, amplitude, and periodic characteristics of China' s climate change over the past 2,000 years, is primarily based on this program' s research results. The homogenized Chinese centennial temperature series dataset was cited in the Third National Climate Change Assessment Report. Multiple program experts served as lead authors for the Third National Climate Change Report and as authors for IPCC assessment reports. Climate model research progress contributed to the establishment of the national major scientific and technological infrastructure "Earth System Numerical Simulation Facility."

3.3 Participation in 2015 Paris Climate Conference Activities Expanded Program Impact

The carbon program organized a side event themed "Tracking Carbon Footprints —Chinese Scientists in Action" at the China Pavilion during the Paris Climate Conference [Figure 2: see original paper], and established a dedicated program exhibition booth in the conference area to showcase Chinese scientists' work and progress in developing carbon budget accounting and climate change response. Multiple media outlets from Canada, France, the United Kingdom, Sweden, and China conducted interviews and reports before and after the conference, generating positive impact.

3.4 Cultivation and Training of Scientific Talent

The carbon program cultivated and trained a scientific talent team with cutting-edge technological capabilities that can address major national strategic needs. The program cultivated and introduced 43 talented individuals including recipients of the National Science Fund for Distinguished Young Scholars, Thousand Talents Program, Young Thousand Talents Program, and National Youth Top-notch Talent Support Program. Additionally, four experts were elected as academicians of the Chinese Academy of Sciences or Chinese Academy of Engineering during their participation in the program.

3.5 Incubation and Acquisition of National Major R&D Projects

The implementation of the Strategic Priority Research Program on Carbon Budget Certification and Related Issues for Climate Change Response fully demonstrates the pioneering nature of such programs. Related research content has been partially included in the Ministry of Science and Technology' s 13th Five-Year Major Research Plan guidelines, such as global change, fragile ecosystem management, and high-performance computing. According to incomplete statistics, 11 experts have applied for and obtained project approvals.

Over the past 25 years, the international community has conducted five unprecedented assessments of global climate change, achieving systematic and in-depth

results that have greatly enhanced scientific understanding of human impacts on global climate change and ultimately led to the formulation of international climate conventions for adaptation and mitigation. Against this international backdrop, the Chinese Academy of Sciences Carbon Program conducted research on greenhouse gas emissions, ecosystem carbon sequestration, climate sensitivity, climate change impacts and adaptation, and green development policy design, completing all tasks with high quality and achieving a series of original results recognized by domestic and international academia. The program has enhanced China' s discourse power in climate change negotiations and supported national decision-making on climate change response. Research results have been incorporated into the IPCC Fifth Assessment Report and the Third National Climate Change Assessment Report, promoting the establishment of related national key R&D programs. The program has also provided important support for China' s climate change adaptation planning and emission reduction actions. The big data and multiple model sequences obtained through program research have laid a necessary foundation for future climate change studies.

Ding Yihui, Researcher, Academician of the Chinese Academy of Engineering. Special Advisor on Climate Change to the China Meteorological Administration, Deputy Director of the National Climate Change Expert Committee. Participated in the compilation of the First through Fifth IPCC Assessment Reports, serving as Vice Chair and then Chair of Working Group I for the Second and Third Assessment Reports. Also participated in the compilation of three National Climate Change Assessment Reports. Received the 1995 National Natural Science Award (Second Class), 2003 National Science and Technology Progress Award (First Class), 2005 National Science and Technology Progress Award (Second Class), 2002 Ho Leung Ho Lee Prize, and the 2005 World Meteorological Organization Award for Outstanding Achievement in Monsoon and Climate Research.

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