# Atmospheric 14CO2 Observations: A New Method for Carbon Emissions Assessment (Postprint)

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## Abstract

As a major carbon-emitting country, China faces the dual challenges of achieving carbon peak and carbon neutrality (hereinafter referred to as "dual carbon" ) objectives and international pressure for carbon emission reduction. Therefore, accurate carbon emission data is crucial for evaluating the "dual carbon" goals and fulfilling international commitments. Reports from the Intergovernmental Panel on Climate Change (IPCC) recommend combining carbon dioxide (CO2) observations with atmospheric inversion to "top-down" validate "bottom-up" carbon emission inventories, and point out that incorporating atmospheric 14CO2 observations can validate carbon emission inventories more accurately. Radiocarbon isotope (14C) is the most accurate tracer for fossil-fuel-derived CO2 and has been widely recommended by the international community for carbon emission assessment. Based on international development trends in atmospheric 14CO2 observations and the urgent domestic situation, this article recommends increasing support to establish an atmospheric 14CO2 observation network; conducting training, standardizing relevant protocols, and actively participating in international exchanges; and promptly initiating research that integrates 14CO2 observations with atmospheric inversion. This would align China' s carbon emission research with international standards, enhance the reliability of carbon emission data, and thereby serve the nation' s "dual carbon" objectives and climate diplomacy negotiations.

## Full Text

## Atmospheric 14CO2 Observation: A Novel Method to Evaluate Carbon Emissions

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## Abstract

As a major carbon emitter, China faces the dual pressures of achieving its carbon peaking and carbon neutrality goals (hereinafter referred to as "dual carbon" goals) and fulfilling international carbon reduction commitments. Accurate and timely carbon emission data are therefore crucial for evaluating progress toward these dual carbon goals and ensuring compliance with international agreements. The Intergovernmental Panel on Climate Change (IPCC) recommends combining atmospheric CO2 observations with atmospheric inversion to "top-down" verify "bottom-up" carbon emission inventories, noting that incorporating atmospheric 14CO2 observations can further improve the accuracy of such verification. Radiocarbon (14C) serves as the most precise tracer for fossil fuel-derived CO2 and has been widely recommended by the international community for carbon emission evaluation. Based on international developments in atmospheric 14CO2 observation and the urgent domestic situation, this paper proposes increased support to establish an atmospheric 14CO2 observation network, training programs to unify relevant standards and enhance international engagement, and prompt initiation of research integrating 14CO2 observations with atmospheric inversion. These efforts will align China' s carbon emission research with international standards, improve the reliability of national carbon emission data, and ultimately support the country' s dual carbon goals and climate diplomacy negotiations.

**Keywords:** radiocarbon, fossil fuel CO2, carbon emissions, carbon peaking and carbon neutrality, new method

## Introduction

Antarctic ice core records demonstrate that atmospheric carbon dioxide (CO2) concentration has varied synchronously with temperature over the past 800,000 years [1]. Since the Industrial Revolution, atmospheric CO2 concentration has increased from 280 ppm to approximately 417 ppm in 2022 [2], while the global average surface temperature has risen by about 1.1°C [3]. Consequently, the international community widely recognizes that global warming is caused by emissions of greenhouse gases such as CO2 and has reached a consensus on reducing greenhouse gas emissions to control global temperature rise. The Paris Agreement sets a target of limiting global temperature increase to well below 2°C, preferably to 1.5°C, and controlling atmospheric CO2 concentration within 450 ppm by 2050, with countries participating in global climate action through "nationally determined contributions." As a major carbon emitter, China faces both its dual carbon goals and international pressure for emission reductions. Therefore, accurate carbon emission data are essential for assessing and ensuring the achievement of these dual carbon goals and fulfilling international commitments.

## 1. Main Methods for Carbon Emission Assessment

### 1.1 Bottom-up Inventory Method

Currently, carbon emission assessments in most countries rely primarily on the “bottom-up” inventory method, which calculates total emissions by multiplying fossil fuel consumption by corresponding emission factors. While this approach is widespread and straightforward, the resulting emission estimates carry significant uncertainties (3%-15%) [4,5], stemming from uncertainties in both emission factors and energy consumption data, particularly for coal. For instance, the IPCC recommends carbon emission factors for different coal types ranging from 0.322 to 0.711 [ ], while recent measurements indicate an average emission factor of 0.499 for coal consumed in China [6]. Applying this revised factor suggests that China’ s cumulative carbon emissions from 2000–2012 were overestimated by approximately 2.9 billion tons of carbon—an amount exceeding China’ s total terrestrial carbon sink. Such large uncertainties significantly hinder accurate assessment of China’ s carbon emissions and international compliance. Uncertainties in fossil fuel consumption data primarily arise from intentional and unintentional statistical errors, with even greater uncertainties (50%-200%) at the urban scale [7] due to incomplete statistical coverage and ambiguous statistical boundaries.

### 1.2 Top-down Observation and Inversion Method

The Paris Agreement also advocates for a “measurable, reportable, and verifiable” (MRV) system to monitor emission changes from energy and fossil fuel-intensive countries. The IPCC’ s latest revised greenhouse gas inventory guidelines specifically include methods for verifying emission inventories through “top-down” atmospheric CO2 concentration inversion, noting that incorporating atmospheric radiocarbon (14CO2) observations can further improve the accuracy of verification results [8]. This top-down approach serves as an important complement to bottom-up inventory methods, providing independent verification and enhancing the reliability of national emission data. Atmospheric inversion requires high-precision atmospheric CO2 concentration data, typically obtained from ground-based stations that offer high accuracy (0.1 ppm) and continuous temporal coverage for long-term monitoring, though with limited spatial representation. In recent years, satellite remote sensing technology has provided large-scale CO2 column concentration data, but these observations are susceptible to orbital constraints, clouds, and aerosols, with lower precision than ground-based measurements [9,10]. Both ground and satellite observations represent mixed contributions from various sources without distinguishing fossil fuel-derived CO2 (CO2ff), making it difficult to validate emission inventories.

Why can atmospheric 14CO2 observations improve inversion accuracy? Conventional atmospheric inversion uses total atmospheric CO2 concentration without distinguishing CO2ff (the primary component of anthropogenic emissions) from biospheric CO2 (CO2bio), preventing direct comparison with inventory-based emissions (mainly from anthropogenic sources). Radiocarbon (14C) serves as the most accurate tracer for CO2ff, far superior to indirect tracers such as CO and NO2. With a half-life of 5,730 years—much shorter than the formation time of fossil fuels—the 14C in fossil fuels has long since decayed away, resulting in CO2ff containing no 14C. In contrast, CO2bio maintains 14C levels close to modern atmospheric concentrations, creating a difference of approximately 100% in 14C values between CO2ff and CO2bio. This large isotopic difference makes 14C the most accurate tool for distinguishing CO2ff. By observing atmospheric 14CO2 values, the concentration of atmospheric CO2ff can be quantified, enabling direct validation of CO2ff concentrations derived from anthropogenic emission inventories and reducing uncertainties in inverted emission estimates. However, atmospheric 14CO2 observation presents technical challenges, including high precision requirements (0.2%) and the inability to conduct online measurements. With a natural abundance of only 1.2$\times10^{-12}$ relative to carbon, 14C requires specialized and expensive accelerator mass spectrometry for high-precision (0.2%) analysis.

## 2. International Trends and Developments in Atmospheric 14CO2 Observation

### 2.1 Origin and Development

Western countries began atmospheric 14CO2 observations in the 1950s to study the effects of atmospheric nuclear weapons testing. The longest continuous record started in 1954 in Wellington, New Zealand [11], with subsequent expansion to numerous global stations. Observations revealed a sharp increase in atmospheric 14CO2 due to nuclear testing, peaking in 1964. Following the 1963 Partial Nuclear Test Ban Treaty, atmospheric 14CO2 levels declined through exchange with oceanic and terrestrial carbon reservoirs. By the late 1980s and early 1990s, nuclear influences had diminished sufficiently for Europe to begin using atmospheric 14CO2 observations to trace urban atmospheric CO2ff variations. Subsequently, atmospheric 14CO2 observation has been widely applied for CO2ff tracing in Europe, America, and other regions [12-15].

### 2.2 International Cases of Using Atmospheric 14CO2 to Assess Emission Inventories

International research demonstrates that combining atmospheric 14CO2 observations with models can evaluate and reduce uncertainties in emission inventories. Point-source emission uncertainties, typically around 20%, can be reduced to approximately 10% when atmospheric simulations incorporate 14C data [15]. At the national scale, more atmospheric CO2ff data from 14C tracing enables more accurate emission inversion. Inversion of monthly US carbon emissions using over 1,000 atmospheric CO2ff data points yields uncertainties of 5%; with 5,000 14C data points, uncertainties decrease to about 3%. Combining atmospheric 14CO2 and CO2 data with inversion models yielded US emissions of 1,653 ± 30 Tg $C \cdot yr^{-1}$ for 2010, with uncertainties below 2% [16,17].

### 2.3 Recognition and Recommendation by International Organizations

Because 14C can accurately quantify fossil fuel contributions to atmospheric CO2, 14C tracing is recognized internationally as an independent and objective method for evaluating carbon emissions. The U.S. National Academy of Sciences (NAS) recommended in 2010 and 2022 that expanding atmospheric 14CO2 observation sites would enhance verification capabilities for emission inventories [18,19]. The World Meteorological Organization (WMO) identified 14C tracing of atmospheric CO2ff as a primary method for assessing carbon emissions in its 2019 greenhouse gas bulletin, recommending that laboratories participating in the Global Atmosphere Watch (GAW) program conduct simultaneous observations of atmospheric CO2 and 14CO2 [20]. The IPCC has incorporated atmospheric 14CO2 observation into its latest revised greenhouse gas inventory guidelines [8], noting that it improves the accuracy of CO2 concentration-based atmospheric inversion and thus enables more accurate assessment of emission inventories.

## 3. Domestic Status and Deficiencies in Atmospheric 14CO2 Observation

### 3.1 Urgency and Current Status of Carbon Monitoring in China

China' s carbon emissions account for approximately one-third of the global total, creating an urgent need to expand carbon monitoring, tracing, and inversion research. Since 1989, China has established long-term atmospheric CO2 concentration monitoring at Waliguan in Qinghai, Shangdianzi in Beijing, Lin' an in Zhejiang, and Longfengshan in Heilonghai [21,22], with some studies inverting atmospheric CO2 column concentrations across East Asia [23]. However, current CO2 monitoring and inversion in China focus primarily on total concentration without distinguishing fossil fuel and biospheric contributions, hindering accurate emission assessment and climate diplomacy. Recognizing the importance of atmospheric 14CO2 observation, China' s Ministry of Ecology and Environment issued the "Carbon Monitoring and Evaluation Pilot Work Plan" in September 2021, requiring pilot cities to conduct atmospheric 14CO2 monitoring.

### 3.2 Progress in Atmospheric 14CO2 Observation in China

Compared with international efforts, China' s atmospheric 14CO2 observation research started relatively late, with domestic applications beginning only in 2010 [24]. Chinese research teams have systematically investigated atmospheric 14CO2 background values and their relationship with emissions, urban CO2ff concentration levels and characteristics, and sources, transport, and relationships with fine particulate matter (PM2.5) [25-31], achieving three major advances. First, they established atmospheric 14CO2 sample collection methods across different timescales and achieved high-precision measurements (better than 0.2% after graphitization and accelerator mass spectrometry analysis), obtaining China’ s atmospheric 14CO2 background values and revealing their variation patterns. This work, based on observations at Waliguan in Qinghai, Qixianling in Hainan, and Taibai Mountain in Shaanxi, has eliminated reliance on foreign background values and enables timely, accurate tracing of China’ s CO2ff. Second, they quantified atmospheric CO2ff concentration levels in major Chinese cities and revealed their spatiotemporal characteristics and influencing factors. Observations show that urban atmospheric CO2ff exhibits higher concentrations in winter than summer, diurnal double-peak patterns, and no significant difference between weekdays and non-working days—distinct from European and American cities. Spatially, urban CO2ff shows higher concentrations in urban centers than suburbs, decreasing from the center of the Guanzhong Basin to its periphery, and higher winter concentrations in northwestern Chinese cities. Multi-year observations in Xi’ an show atmospheric CO2ff decreased from 40.1 ± 3.8 ppm during 2011-2013 to 25.7 ± 1.1 ppm during 2014-2016, while PM2.5 concentrations simultaneously decreased from 123.5 ± 9.5 $\mu g \cdot m^{-3}$ to 69.6 ± 8.4 $\mu g \cdot m^{-3}$, demonstrating that the “Air Ten Measures” implemented since September 2013 achieved dual reductions in both air pollutants and CO2ff. Third, they resolved sources and transport impacts of CO2ff in typical cities and identified synchronous variation with PM2.5. Combining 13C isotope analysis revealed that winter CO2ff in Xi’ an originates primarily from coal combustion (54%-70%), while Beijing’ s winter CO2ff comes mainly from natural gas combustion (55% ± 9%). Coupled regional meteorology-atmospheric chemistry modeling indicates Xi’ an’ s CO2ff originates primarily from emissions within the Guanzhong Basin, whereas Beijing’ s CO2ff is significantly influenced (approximately 30%) by southeasterly transport. Research also shows widespread correlation between urban CO2ff and PM2.5 concentrations, with CO2ff significantly elevated during haze episodes, providing support for China’ s current synergistic pollution and carbon reduction strategies.

### 3.3 Deficiencies in Atmospheric 14CO2 Observation in China

Despite progress, China’ s atmospheric 14CO2 observation faces several shortcomings. While 14C tracing has yielded atmospheric CO2ff concentration levels, these cannot be directly compared with inventory-based emission estimates (in tons) due to differing units. Although one team combined CO2 observations with atmospheric inversion to study emissions in the Taiyuan-Jinzhong region [32], the prior emission inventory used in their inversion has not been validated by 14C tracing. Overall, China lacks research integrating 14CO2 observation with atmospheric inversion for quantitative emission estimation. Furthermore, accurate carbon sink inversion requires precise fossil fuel emission data, necessitating development of a “14CO2-CO2” dual-tracer inversion system that can more effectively reduce errors from inaccurate separation of CO2ff and CO2bio during assimilation, enabling more precise emission inversion for China. Additionally, atmospheric 14CO2 observation requires specialized expertise and high precision (0.2%), necessitating unified training programs and standardized observation and measurement protocols. Regular domestic and international intercomparisons, along with active exchange of latest experiences and results with international colleagues, would expand China' s influence in this field. Finally, the high cost of 14C analysis and current inability to conduct online atmospheric 14CO2 observation require long-term commitment and increased support from government agencies and research institutions at all levels.

## 4. Recommendations

Based on current international carbon reduction trends and research frontiers, atmospheric 14CO2 observation represents a critically important and urgent task for China' s dual carbon agenda. We propose four recommendations:

First, establish a comprehensive atmospheric 14CO2 observation network across China as soon as possible. Given China's vast territory and limited atmospheric 14CO2 data, we recommend maximizing the establishment of observation sites covering various location types to fully reveal fossil fuel and biospheric contributions to atmospheric CO2, map the distribution of CO2ff and CO2bio across China, and provide crucial baseline data for atmospheric inversion research.

Second, conduct unified training and standardization. Due to the specialized nature and high precision requirements (0.2%) of atmospheric 14CO2 observation, we recommend implementing training programs to unify observation standards and measurement methods, organizing regular domestic intercomparisons, actively participating in international intercomparisons, and regularly comparing data with foreign background atmospheric 14CO2 observations to facilitate exchange of latest experiences and expand China' s influence.

Third, increase support at all levels. While 14C analysis costs are high and atmospheric 14CO2 cannot currently be measured online, this is long-term work requiring sustained commitment. We recommend gradually incorporating atmospheric 14CO2 observation into greenhouse gas monitoring operations, with research institutes leading the development of unified technical standards for sample collection, measurement, and quality control, while local governments provide support for site establishment, sampling, personnel, and funding.

Fourth, promptly integrate 14CO2 observation with atmospheric inversion to conduct national and regional emission inversions that validate inventory-based emissions and improve the reliability of China' s carbon emission data.

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The carbon emission factor for coal refers to carbon emissions per ton of coal burned (tons of carbon per ton of coal).

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