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Near-Real-Time Carbon Emission Accounting Technology Toward Carbon Neutrality

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ABSTRACT

Climate change is the greatest environmental threat to humans and the planet in the 21st century. Global anthropogenic greenhouse gas emissions are one of the main causes of the increasing number of extreme climate events. Cumulative carbon dioxide (CO_2) emissions showed a linear relationship with cumulative temperature rise since the pre-industrial stage, and this accounts for approximately 80% of the total anthropogenic greenhouse gases. Therefore, accurate and reliable carbon emission data are the foundation and scientific basis for most emission reduction policymaking and target setting. Currently, China has made clear the ambitious goal of achieving the peak of carbon emissions by 2030 and achieving carbon neutrality by 2060. The development of a finer-grained spatiotemporal carbon emission database is urgently needed to achieve more accurate carbon emission monitoring for continuous implementation and the iterative improvement of emission reduction policies. Near-real-time carbon emission monitoring is not only a major national demand but also a scientific question at the frontier of this discipline. This article reviews existing annual-based carbon accounting methods, with a focus on the newly developed real-time carbon emission technology and its current application trends. We also present a framework for the latest near-real-time carbon emission accounting technology that can be widely used. The development of relevant data and methods will provide strong database support to the policymaking for China's "carbon neutrality" strategy. Finally, this article provides an outlook on the future of real-time carbon emission monitoring technology.

1. Introduction

The total global anthropogenic greenhouse gas emissions have reached the highest levels since measurements began in recent years. This is likely to be the main driving force for climate change [1]. Greenhouse gas emission inventories have always been a critical scientific basis for the construction of climate models, the formulation of national emission reduction policies, and international negotiations [2]. To slow down climate change and achieve sustainable development goals, worldwide efforts have proposed a series of global emission reduction agreements such as the Kyoto Protocol and the Paris Agreement since the end of the 20th century [3]. Energy activities based on fossil energy consumption and cement production are the most important sources of carbon dioxide (CO_2) emissions from human activities, and their emissions account for approximately 80% of the total greenhouse gas emissions from human activities [4]. Therefore, accurate and reliable CO_2 emission data from energy activities are the benchmark for the formulation of emission reduction policies and targets, which are essential for carbon emission-related scientific research and policymaking [3].

As the world's largest developing country, China has been the largest fossil energy consumer and CO_2 emitter from 2007 to 2009 [5]. China's CO_2 emissions continued to grow rapidly, although emissions reached a plateau in 2013 [6]; it continues to be the world's leading energy consumer and CO_2 emitter [7]. After 2018, China's annual growth rate of carbon emissions exceeded 2% for two consecutive years [8,9], but the annual growth rate of global carbon emissions was only 0.1%. Therefore, China faces a great pressure to reduce emissions from the international community.

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China plays a critical role in the international action of climate change, given its fast-growing economy and giant industry sector. In 2005, the Chinese government released the *1996 IPCC Guidelines for National Greenhouse Gas Inventories* [10] and *2006 IPCC Guidelines for National Greenhouse Gas Inventories* [11] issued by the Intergovernmental Panel on Climate Change (IPCC). As required by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, the 1994 and 2005 greenhouse gas inventories were submitted to the United Nations [12]. Since 2015, the Chinese government has emphasized the statistical work on carbon emission accounting. It has been clearly stated in the *Outline of the National Medium and Long-term Scientific and Technological Development Plan* [13], *The Twelfth Five-Year Plan for National Economic and Social Development* [14], *The Special Plan for Science and Technology Development to Address Climate Change in China's Twelfth Five-Year Plan* [15] and *The National Climate Change Plan to Address Climate Change (2014–2020)* [16] that China's climate change-related statistics need to be strengthened, and a scientific framework that integrates complete and unified statistics needs to be developed to objectively reflect China's active response to climate change. Establishing and improving the greenhouse gas emission statistical system is not only an urgent need for China to effectively fulfill its international obligations, but also an important guarantee to take preemptive actions in international negotiations on climate change [17]. In 2016, the Chinese government responded to climate change and sustainable development as a national strategy and formulated a relative emission reduction target that will reduce carbon emission intensity (carbon emissions per unit of gross domestic product (GDP)) by 60% compared with 2005 [18]. China's CO_2 emission reduction targets are set in the 14th Five-Year Plan in 2021. At the United Nations Climate Change Conference in September 2020, President Xi Jinping made it clear that China's CO_2 emissions will strive to reach its peak by 2030 and achieve carbon neutrality by 2060 [19].

As part of the global endeavor toward "carbon neutrality," an analysis of China's current carbon emissions shows that although China's per capita carbon emissions have exceeded the global average, the per capita cumulative carbon emissions are far below that of developed countries, which suggests that achieving the "carbon neutrality" goal is more difficult than expected. China needs to have a better layout and implementation of emission reduction actions and policies, which puts forward higher requirements for the timeliness and accuracy of carbon emission accounting and monitoring data. Based on the current existing carbon emission accounting methods, this article introduces the real-time carbon emission technology proposed for major countries (emission bodies) in the world. The technology achieves near-real-time (day or hour level) accurate emission accounting for China and other major countries around the world for more comprehensive comparisons. This timely and accurate carbon accounting framework inherits the advantages of previous methods and provides timely data in support of the carbon-neutral goal.

2. Methods and applications of carbon accounting

2.1. Production-side carbon accounting

National CO_2 emission accounting is the basis for implementing emission reduction measures, formulating national emission reduction strategies, and conducting international verification and evaluation [3]. To this end, international organizations such as the IPCC have formulated a method for estimating national CO_2 emissions based on the energy consumption of carbon-containing fossil fuels and the carbon content of the corresponding fossil fuel itself [20], that is, to compile carbon emissions through activity data and corresponding emission coefficients. This accounting method is widely used worldwide. Specifically, there are two types of carbon emission accounting methods recommended by the IPCC: the reference and sectoral approaches. The reference approach is to estimate CO_2 emissions through the total energy consumption of the country, and the total energy consumption is the difference between energy production, import and export, and inventory. The sectoral approach calculates the CO_2 emissions of the sub-sectors according to the energy consumption of the sub-sectors, and then the total carbon emissions of the country are obtained [3]. Because the calculation method recommended by the IPCC uses primary energy data carbon accounting (accounting for factors such as primary energy conversion, energy loss in the process of fuel washing, and fuel non-energy use), and primary energy is at the production end of the energy supply chain, this calculation method is also called production-side carbon accounting. Table 1 lists the current production-side carbon accounting authorities.

Carbon emissions can be disaggregated into fossil energy carbon emissions and industrial process carbon emissions:

$$E_t = E_{ff} + E_{in} \tag{1}$$

where E_t, E_{ff}, and E_{in} represent total emissions, emissions from fossil fuels, industrial process, respectively.

Fossil fuel emissions can be calculated using Eq. (2):

$$E_{ff} = A \times F = E \times C \tag{2}$$

where H, C_h, and O represent the heating value, carbon content per unit heat, and oxidation rate, respectively.

Given the relationship between emission factors, quality, property, and combustion efficiency of fuels, the emission factor can be further disaggregated:

$$F = H \times C_h \times O \tag{3}$$

where H, C_h, and O represent the heating value, carbon content per unit heat, and oxidation rate, respectively.

Therefore, fossil fuel emissions can be estimated using Eq. (4):

$$E_{ff} = A \times H \times C_h \times O \tag{4}$$

The industrial process mainly includes cement production, with an emissions calculation similar to that of fossil fuels, formulated as Eq. (5):

$$E_{in} = A \times F \tag{5}$$

From the calculation equations, we know that the uncertainties of CO_2 emission estimates mainly come from two aspects: activity data (energy consumption or industrial production) and emission factors.

A targeted assessment of China's carbon emissions is essential, given its significant role in global emissions. In 2011, the Chinese Academy of Sciences launched a strategic pilot technology special, "Carbon budget certification and related issues in response to climate change." Among them, the task of "energy consumption and emissions from cement production" has formed a general database of China's energy use and cement production, a visual system has been constructed, and the consumption and oxidation factors of different energy types in China are obtained by integrating data from different utilization industries, thereby obtaining the total CO_2 emissions of different energy types in China [17,22]. Using the carbon emission factors obtained in Ref. [22], the China Emission Accounts & Datasets (CEADs) team calculates and publishes the corresponding carbon emission inventories based on the annual *China Energy Statistical Yearbook* and the statistical data in the provincial and municipal energy statistical yearbooks [6,23]. Cai et al. [24] have systematically developed a bottom-up method for accounting for greenhouse gases in Chinese cities, which

Table 1
Global production-side carbon accounting authorities [21].

Research institute and database	Data source	Year range
Carbon Dioxide Information Analysis Centre (CDIAC)	https://cdiac.ess-dive.lbl.gov/	1951–2014
European Commission's Joint Research Centre (JRC)/ Netherlands Environmental Assessment Agency (PBL)		
Emissions Database for Global Atmospheric Research (EDGAR)	https://edgar.jrc.ec.europa.eu/	1970–2019
International Energy Agency (IEA)	https://www.iea.org/	1990–2018
US Energy Information Administration (EIA)	https://www.eia.gov/	1949–2018
World Bank	https://data.worldbank.org/	1960–2018
United Nations Framework Convention on Climate Change (UNFCCC)	https://unfccc.int/	1990–2019
World Resources Institute (WRI)	https://datasets.wri.org/	1990–2018

reduces the uncertainty of activity levels and emission factors, named the Greenhouse Gas Emissions Grid Data Inventory (CHRED) with a spatial resolution of 1 km. Xu et al. [25] employed a bottom-up method to account for global black carbon emissions from 1960 to 2017 and compared the updated results with other existing inventories (including Peking University (PKU)-2020 and Emissions Database for Global Atmospheric Research (EDGAR)), with other emission inventories-related works (including the PKU-CO_2 inventory that uses a subnational disaggregation method (SDM) based on the combustion rates for different fuel types compiled at the global or national level and emission factors) [26–30]. Wang et al. [31] and Liu et al. [32] developed provincial-data-based emission inventories (Nanjing University (NJU)-CO_2) using a sectoral approach under the guidelines of the IPCC. It is noteworthy that the China carbon emission inventory developed by the above research is entirely on an annual scale, with low time resolution and a time lag of one year or more.

2.2. Consumption-side carbon accounting

Clarifying carbon emission responsibilities is an indispensable stage in international negotiations on global climate initiatives. Developed countries may use their capital and technological advantages to transfer polluting industries with the highest CO_2 emissions to underdeveloped regions, thereby reducing their own direct CO_2 emissions and transferring emission reduction obligations to underdeveloped regions. Researchers have proposed a consumption-based CO_2 accounting method (accounting for the potential "carbon leakage") to take into consideration the emissions caused by consumption activities and fairly represent the actual CO_2 emissions of different countries. Currently, the consumption-based carbon accounting method (also known as the carbon footprint) has become an effective method for calculating CO_2 emissions. Specifically, consumption-based carbon accounting mainly includes process analysis (i.e., life cycle assessment) (Table 2) and input–output (IO) analysis.

The life cycle assessment method is a "bottom-up" method, which aims to track the direct and indirect impacts of the product on the environment ("from the cradle to the grave"). By collecting the carbon emission data generated by the substances and activities covered by the entire product process, the life cycle assessment method can estimate the carbon emissions over the entire life cycle of a particular product. Many carbon footprint accounting standards have been built based on this method to evaluate environmental impacts.

The IO method is a "top-down" method, which aims to measure CO_2 emissions at the national/regional or sectoral level through the dependence between inputs and outputs of various economic sectors reflected in the IO table. Generally, the total carbon emissions at the consumer end are equal to the direct carbon emissions of the region minus the emissions of products exported from the local region to other regions, and the emissions in other regions caused by the production of imported local products [42]. Many studies have investigated embodied carbon emissions in international trade based on the IO method. For example, Meng et al. [43] used the IO method to analyze the impact of the rise in South–South trade on carbon emissions in developing countries, and the results showed a trend of carbon emissions shifting from China to underdeveloped regions such as Southeast Asia from 2004 to 2011. China-related studies have analyzed the distribution of China's global carbon footprint in 2012 and found that China's international carbon footprint was concentrated in traditional manufacturing centers, including the Yangtze River Delta, the Pearl River Delta, and the North China Plain. These regions account for approximately 1% of China's land area, but they contribute to approximately 75% of the global carbon footprint [44]. In recent years, climate justice has received increasing attention. Mi et al. [45] calculated the household carbon footprint of 12 income groups in 30 regions of China in 2012 using the multi-regional IO

Table 2
Representative carbon footprint accounting standards based on life cycle analysis (LCA).

Carbon footprint accounting standard	Institute of publication	Released year
Product-level		
Publicly Available Specification 2050 [33]	British Standard Institution (BSI)	2008
Greenhouse Gas Protocol [34]	World Resource Institute (WRI) and World Business Council for Sustainable Development (WBCSD)	2011
ISO14067 [35]	International Organization for Standardization (ISO)	2013
Organization-level		
Greenhouse Gas Protocol [36]	WRI and WBCSD	2004
ISO 14064-1 [37,38]	ISO	2006, 2018
ISO 14069 [39]	ISO	2013
ISO 14072 [40]	ISO	2014
Comprehensive-level		
Publicly Available Specification 2060 [41]	BSI	2014

method (MRIO) of environmental expansion and analyzed carbon inequality through the carbon footprint as well as the Gini coefficient. The results showed that the top 5% of income groups contribute 17% of the household carbon footprint, while the lowest income groups (about 50% of the sample) contribute only 25% of the household carbon footprint. After the outbreak of the coronavirus disease 2019 (COVID-19) epidemic in 2019, the IO method was used to analyze the impact of the epidemic on carbon emissions, which provided a new perspective for existing research. For example, a recent study showed that compared with the "no epidemic" baseline scenario, the global economic sector's carbon emissions are projected to fall by 3.9%–5.6% in the next five years (2020–2024). Since the global economy is interdependent through the supply chain, even if the blockade policy is not adopted, the restriction of production activities in one economy will also lead to a reduction in carbon emissions in other countries [46].

2.3. Real-time/near-real-time and in-situ carbon accounting

To meet the increasing demand for fine-grained data, real-time/near-real-time accounting methods and related technologies have drawn more attention in recent years. Multiple studies have used ground monitoring data (such as continuous emission monitoring system (CEMS) and Fourier transform spectrometer (FTS)) and remote sensing satellite data (such as the greenhouse gases observing satellite (GOSAT) and the tropospheric monitoring instrument (TROPOMI)) to analyze the impacts of natural disasters and pandemics such as COVID-19 on the global economy and greenhouse gas emissions. For example, based on the relationship between tropical forest cover and carbon emissions, Doblas et al. [47] developed an early warning system (EWS) for deforestation based on satellite (Sentinel-1) real-time monitoring and the relationship between carbon emissions and tropical forest cover with a data accuracy of 94.36%. The system is expected to help in the real-time monitoring of emissions related to land change in the future. In addition, by monitoring the carbon emissions of tropical rainforests, existing research has achieved near-real-time tracking and early warning of forest fires, illegal mining, and other forest destruction behaviors [48–51].

The outbreak of the COVID-19 pandemic has put forward an urgent need for the development of global real-time carbon emission technology. The value of research on real-time carbon emission technology in the field of pandemic impact has gradually been awarded attention and recognized by the academic community [52–57]. Based on the urban traffic carbon emission data collected by the ground monitoring station, Tian et al. [58] found that Canada's carbon emissions continued to decrease in 2020 and reached its lowest value in April. Lian et al. [59] combined data from six city-level real-time ground monitoring systems (CEMS) and Bayesian methods to measure CO_2 posterior emissions during the COVID-19 pandemic in Paris, thereby obtaining human sources during the first and second closures of the city because of COVID-19. The emission reduction of CO_2 relative to the same period in 2020. Liu et al. [60] used vehicle-mounted measuring instruments to track carbon emissions during the COVID-19 epidemic in Beijing in real time, and the results showed that the CO_2 concentration during the COVID-19 epidemic was reduced by (41 ± 1.3) ppm ($1\ \text{ppm} = 1\ \text{mg}\cdot\text{L}^{-1}$) and (26 ± 6.2) ppm, respectively, on weekdays and holidays compared to before and after the epidemic, and there was no significant difference between weekdays and holidays. Turner et al. [61] used sensors to conduct real-time atmospheric observations in the San Francisco Bay Area, the first shelter-in-place in the United States. The data showed that human-source carbon emissions were reduced by 30% during the COVID-19 pandemic, which can be attributed to the reduction (48%) of traffic volume, thus laying a scientific foundation for local vehicle electrification.

Remote sensing satellite data and atmospheric inversion models can help to further improve the accuracy of CO_2 concentration calculations. Based on TROPOMI satellite observation data, Zheng et al. [62] estimated the dynamic trend of China's provincial carbon emissions during the COVID-19 epidemic. The results showed that from January to April 2020, China's CO_2 emissions decreased by 11.5% compared to the same period in 2019. Subsequently, due to rapid economic recovery activities, carbon emissions have returned to pre-epidemic levels. City-level studies in Beijing showed that human-source CO_2 emissions related to the lockdown policy exhibited a downward trend during the epidemic, and ground-based Fourier transform infrared spectroscopy (FTIR) data showed that carbon emissions were reduced by 14.2%. GOSAT satellite data showed a 15% reduction in carbon emissions [63]. Buchwitz et al. [64] used Orbiting Carbon Observatory-2 (OCO-2) and GOSAT observation data to estimate the emission reduction of human-source CO_2 emissions in east China during the COVID-19 pandemic. The results showed that in March and April 2020, the CO_2 emission reduction was approximately 10% ± 10% (standard deviation (std.)). However, the data showed large monthly differences, and the analysis results of satellite datasets have significant differences, which indicates that the current satellite data quality cannot achieve the required accuracy of real-time observation.

2.4. Comparison of existing carbon accounting methods

The three existing carbon accounting methods have individual advantages and disadvantages (Table 3). Among them, the production-side carbon accounting method is easy to use for calculations and has a high penetration rate. Worldwide official authorities use production-side carbon accounting methods to measure carbon emissions. Under the premise of clarifying the emission sources, their data are applicable to many scales and can usually be used for macro-, meso-, and micro-studies. It should be noted that this accounting method is mainly based on carbon emission factors and energy statistics. The uncertainties of carbon emission factors make it difficult to verify the reliability of the calculation results; also, the release of energy statistics often has a long time lag (one year or more) and generally only at an annual scale. Therefore, carbon accounting methods based on the production side have difficulty supporting more fine-grained carbon emissions research. The consumer-side carbon accounting method also has the advantages of simple calculation and high penetration rate, but its data quality requirements are high; therefore, the calculation results have greater uncertainty. In addition, the collection of product activity data and the release of IO tables have a certain time lag, and the temporal and spatial resolution is also low; thus, high-fine-grained dynamic research cannot be carried out. Although the results of the measured accounting method are more accurate, they require continuous and high-coverage monitoring of carbon emissions. However, it is difficult to achieve cost-effective large-scale tracking using existing ground-monitoring technology and remote sensing satellite technology.

3. A global near-real-time carbon emission system

In the context of global countries taking climate actions and successively announcing "carbon neutral" plans, it is necessary to carry out real-time and high-frequency monitoring of carbon emissions, to understand the dynamic trends of carbon emissions, and to timely and reliably assess the impacts of various climate policies. Current carbon emission accounting methods have two major technical problems that need to be overcome: ① The carbon emission dataset has a time lag of one year or more, and ② there is no

Table 3
Comparisons of existing accounting methods.

Carbon accounting methods	Input variables	Advantages	Limitations	Main applications
Production-side carbon accounting	Activity level data and emission factors	Easy calculation; high-cover applications adaptable to multi-scales (micro-, meso-, and macro-scales)	Huge uncertainties of emission factors; time lag of more than one year; low spatiotemporal resolution; time and cost consuming is low due to very mature techniques	Mainstream climate change research and reports
Consumption-side carbon accounting				
Process analysis method/life cycle assessment	Production activity data and emission factors	Detailed calculation; high-cover applications adaptable to microscales	Huge statistical error; huge uncertainties of emission factors; results with low accuracy; low spatiotemporal resolution; time and cost consuming is low due to very mature techniques	Carbon footprint research of products
IO method	IO tables and carbon emission data	Easy calculation	Huge uncertainties of data quality; low continuity of data; time lag of more than one year; low spatiotemporal resolution; limited adaptable scale (only macroscale); time and cost consuming is possibly high due to complicated mathematics encountering multi-country analysis	Trade-embodied carbon (footprint) research
Real-time/near-real-time and *in-situ* carbon accounting	Air flow and CO_2 concentration conversion factors	Results with high accuracy	High cost; low rate of application; time and cost consuming dependable on the specific research	Ecological degradation/disaster impacts research; COVID-19 impacts related research

day-level or hour-level carbon emission data. Based on the background of carbon neutrality and the requirements of high temporal and spatial resolution data, this technical system has developed a set of real-time carbon emission accounting methods based on sectoral activity level data, which can be used to calculate global carbon emissions in real-time or near-real-time, and generate a set of global daily carbon emissions datasets for major countries and subsectors, thereby overcoming the above technical problems [65,66].

A real-time carbon emission system underpins a set of carbon emission accounting methods based on sectoral activity data (Fig. 1). Emissions from countries around the world are divided into six main sectors according to their sources of carbon emissions: electricity, industry, residential consumption, ground transportation, aviation, and shipping. From the general accounting method for carbon emissions, the following equation is deduced:

$$E_t = \sum\nolimits_{energy}(A_{energy} \times F_{energy}) \tag{6}$$

where A_{energy} and F_{energy} represent activity data and emission factor for each sector, respectively.

As the energy consumption structure within the sector is relatively stable, the activity data and emission factors of fuel can be replaced with the activity data and emission factors of the sector (A_{sector} and F_{sector}) to obtain a set of carbon emission accounting methods based on sector activity data:

$$E_t = \sum\nolimits_{sector}(A_{sector} \times F_{sector}) \tag{7}$$

The activity data of one sector is the data related to the energy consumption of the corresponding sector that can reflect the actual activity level of the production of that sector (see activity data in the IPCC method). The sectoral carbon emission factor depends

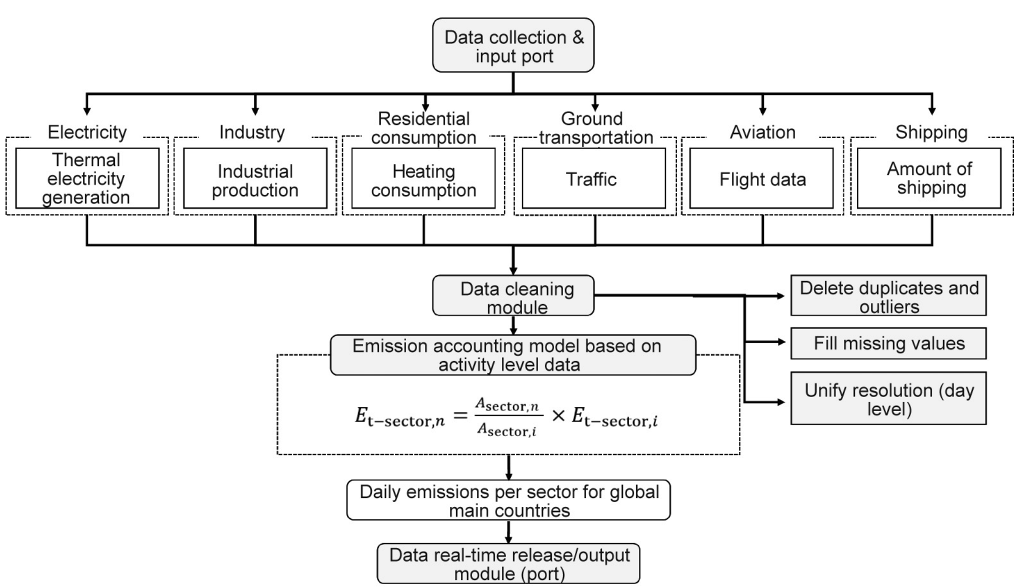

Fig. 1. Near-real-time carbon emission system framework. $E_{t-sector,n}$, $A_{sector,n}$, $A_{sector,i}$, $E_{t-sector,i}$ represent total emissions for one sector for the *n*th day, activity data for one sector for the *n*th day, activity data for one sector for the *i*th day, and total emissions for one sector for the *i*th day, respectively.

on the sector's structure of fuel consumption and the emission factors of those fuels. Because the emission factors remain stable for a certain time period, the sectoral emission factors are assumed to remain unchanged, and the uncertainty of this assumption is considered in the uncertainty-related calculations.

Methodologically, relying on the assumption that the sectoral emission factors remain unchanged, a real-time carbon emission system further proposes a set of carbon emission accounting methods based on departmental real-time activity data. First, publicly available and updated real-time data on various sectoral activities are collected in real time. For example, the main source of carbon emissions in the power sector is the use of fossil fuel emissions in the process of thermal power generation, such as coal, oil, and natural gas. Therefore, thermal power generation (or power generation) can be used to characterize the activity data of the power sector. The main sources of emissions in the ground transport sector are fossil fuels, such as automobile consumption oil. Therefore, the traffic volume can be used to characterize the activity data of the ground transportation sector. The specific activity level data of each department is listed in Table 4.

Data cleaning steps were performed after the data selection. The steps were as follows: ① remove duplicates, ② eliminate outliers (greater than four standard deviations), ③ use linear interpolation to supplement missing values, and ④ change the time resolution of data, which is unified daily. Then, we substituted the cleaned data of each sector into the above-mentioned carbon emission accounting model based on sectoral activity data and used Eq. (7) for calculation. As the sectoral carbon emission factors remain unchanged, therefore:

$$E_{\mathrm{t-sector},n} = \frac{A_{\mathrm{sector},n}}{A_{\mathrm{sector},i}} \times E_{\mathrm{t-sector},i} \tag{8}$$

where $E_{\mathrm{t-sector},n}$, $A_{\mathrm{sector},n}$, $A_{\mathrm{sector},i}$, and $E_{\mathrm{t-sector},i}$ represent total emissions for one sector for the nth day, activity data for one sector for the nth day, activity data for one sector for the ith day, and total emissions for one sector for the ith day, respectively.

Finally, the daily carbon emissions of major countries and subsectors in the world can be obtained and released in real time through the data output port. Compared with the current carbon accounting method, real-time carbon emission technology has the following advantages: It uses the previous carbon emission accounting method based on fossil fuel consumption and proposes a set of carbon emission accounting methods that can reflect the energy consumption level of the sector based on various production and social data. The current carbon emission method can only perform annual emissions accounting for regional-level emissions, while the real-time carbon emission system can calculate sub-sectoral carbon emission inventory data with day-scale resolution, and carbon emission data generated by the current carbon emission method generally have a time lag of one year or more. The real-time carbon emission system improves the ability to update and release carbon emission data to a near-real-time level. It collects all kinds of activity level data in real time, calculates carbon emissions in real time in the carbon emission accounting model based on sectoral activity level data, and updates and publishes carbon emission data in real time through the data output interface. Data updates were published on the Carbon Monitor website[†].

The uncertainties of this technology have been discussed in detail in Ref. [65] (Table 5).

To date, real-time carbon emission technology has been widely used in dynamic monitoring of carbon emissions and research on the impact of the COVID-19 epidemic. Based on the carbon monitor data released by the real-time carbon emission system, Liu et al. [66] conducted a near-real-time monitoring of the CO_2 emissions of different sectors in major countries around the world, and the results showed that, compared to the same period in 2019, the global CO_2 emissions in the first half of 2020 reduced by 8.8% (−1551 Mt CO_2). Based on US state-level real-time carbon data derived from carbon monitors, the study reported daily fossil fuel carbon emissions data from January 2019 to December 2020 and analyzed the impact of the COVID-19 epidemic on US carbon emissions. The results showed that the epidemic has drastically but temporarily reduced carbon emissions, and the specific range varied greatly owing to the strictness of public health policies in each state [67]. The Chinese provincial real-time database inherited from the carbon monitor database tracks the dynamic trends of CO_2 emissions in three sectors (power, industry, and transportation), and estimated the CO_2 emissions in Tibet for the first time. The results showed that the provincial power sector's carbon emissions themselves have evident seasonal characteristics, and the trends of the industrial sector in the north and south of the Yangtze River are evidently different and the transportation sector is more affected by holidays [68]. A breakdown of the transportation sector shows that the sector's carbon emissions in the first half of 2020 endured a rapid decline and subsequently

Table 4
Sources of carbon emissions and selection of activity data for each sector.

Sector	Source of carbon emissions	Activity data
Electricity	Thermal fossil fuel consumption	Thermal electricity
Industry	Fossil fuel consumption (e.g., steel production in high temperature) and industrial process (e.g., cement production)	Industrial production
Residential consumption	Fossil fuel consumption for residents	Heating consumption
Ground transportation	Fossil fuel consumption for vehicles	Traffic
Aviation	Fossil fuel consumption for aviation	Flight data
Shipping	Fossil fuel consumption for ships	Amount of running ships

Table 5
Uncertainties for each sector.

Sector	Sources of uncertainty	Uncertainty
Power	Inter-annual variability of coal emission factors and changes in mix of generation fuel in thermal production	±14.0%
Ground transportation	Assumption that the relative magnitude in car counts (and thus emissions) follow a similar relationship with TomTom congestion index in Paris	±9.3%
Industry	Monthly production data	±36.0%
Residential consumption	Comparison with daily residential emissions derived from real fuel consumption in several European countries	±40%
Aviation	The difference in daily emission data estimated based on the two methods (flight route distance/the number of flights)	±10.2%
International shipping	International Marine Organization (IMO)	±13.0%
Projection of emissions growth rate in 2019	Combination of the reported uncertainty of the projected growth rates and the EDGAR estimates in 2018	±0.8%
EDGAR emissions in 2018	–	±5.0%
Overall	–	±7.2%

[†] https://carbonmonitor.org.

rebounded. The second wave of the epidemic resulted in another round of emission reduction [69].

4. Conclusions and outlook on future research

Owing to the limitations of existing carbon emission accounting approaches, the near-real-time carbon emission technology reviewed in this article aims to address these issues by solving technical problems and overcoming the shortcomings of the current methods, thereby providing basic data support for the "carbon neutral" strategy. At the same time, under the premise of ensuring data accuracy, it lays a solid scientific foundation for China's finer time-grained carbon emission monitoring. This real-time carbon emission technology has been widely recognized by domestic and international academic communities (e.g., *The Emissions Gap Report 2021* [70] sources carbon monitor data. The major advantage of this technology is the capability to monitor and track carbon emissions in real time on a multi-national scale at the multi-sectoral level, and it permits a more systematic comparison between the major carbon-emitting countries on a daily basis. Furthermore, this near-real-time accounting approach may be used as an important reference in international climate change-related negotiations. Theoretically, this technology can bridge the gap in the transition from a one- or two-year time lag of data statistics to near-real-time monitoring, based on carbon accounting methods recommended by the IPCC, and through reasonable approximations (e.g., emission factors) and an expansive volume of data collection, contributing to the rapid responses for carbon monitoring in China. Nevertheless, barriers exist for both the techniques and data. Continuous yearly updating of carbon emissions data remains a challenge for some countries. Specifically, new data sources are needed if some currently used data sources stop updating or become unreliable; thus, new methods adaptable to these newly utilized data sources urgently need to be developed and deployed. The barriers could be gradually ameliorated as more data sources are open-sourced or developed by researchers worldwide, and our understanding of monitoring mechanisms and methodologies deepens (e.g., aid by monitoring provided by the carbon satellites), contributing to the narrowing of uncertainties in near-real-time monitoring.

The future development and application of near-real-time carbon emission technology are projected to focus on the following aspects: ① the monitoring of near-real-time CO_2 emission (GEOS-CF) [71,72] and the development of a real-time human-source carbon emission monitoring system [73] to reveal the anthropogenic carbon emission fluctuations, ② the development of real-time carbon emission technology based on the consumer end to capture the embodied carbon emission flow due to international trade with higher spatial and temporal resolution accounting for the life cycles of products, and ③ the integration of satellite-based "top-down" data and approaches. Multiple international carbon satellite projects (e.g., the Chinese Academy of Sciences' International Partnership Project, International Carbon Satellite Observation Data Analysis Cooperation Program (Phase II)) offer great opportunities for more accurate monitoring of CO_2 concentration on a global scale. More comparative studies are needed to calibrate the "bottom-up" carbon accounting approach using satellite data. Collectively, further developments of near-real-time carbon emission technology are needed to provide more accurate and timely data support for a better understanding of global climate change.

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Authors' contributions

Zhu Liu conceptualizes this review. Taochun Sun writes the original manuscript with the help of Piyu Ke, Chenxi Lu, and follows the suggestions from Zhu Deng. Ying Yu revises the original manuscript. Da Huo and Xiang Ding provides exquisite language polishing to this review.

Compliance with ethics guidelines

Zhu Liu, Taochun Sun, Ying Yu, Piyu Ke, Zhu Deng, Chenxi Lu, Da Huo, and Xiang Ding declare that they have no conflict of interest or financial conflicts to disclose.

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