A carbon-monitoring strategy through near-real-time data and space technology

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In this perspective, we proposed an innovative strategy that coupled near-real-time emission data with satellite observations to make a reliable and precise global carbon-monitoring system.

With nations pledging net-zero emissions by 2050, tracking dynamics of anthropogenic carbon emissions is proving to be essential for global climate change governance and carbon neutrality achievement. Critical challenges remain in the timely, precise, and robust monitoring of carbon emissions given that the anthropogenic carbon emissions are estimated by the emission accounting inventories (e.g., emission datasets of IEA) that are based on energy statistics rather than measured directly. These “bottom-up” estimates, which are often related to incompleteness of energy statistics, uncertainty in emission factors, and inconsistencies in data quality between regions, highlight the urgent need for technology and research paradigm innovation.

On the other hand, the “top-down” space observation technologies (satellite and its integrated observation system) provide a potential measurement and verification solution that has been rapidly developed, taking advantage of its real-time, continuous, large-scale, and repeated observations. Europe (SCIAMACHY), Japan (GOSAT 1/2), the United States (OCO2/3), Canada (GHGSat-D), and China (TanSat/Gaofen-5) have successively launched satellites with CO2 concentration observation capability in the last two decades.

However, gaps remain in tracking anthropogenic emissions from space independently for several CO2 features and satellite limitations. (1) The satellites measure column-averaged dry air mole fraction of CO2 (XCO2) instead of CO2 emissions, which means conversion is needed to trace the enhancement in XCO2 from human-related CO2 emissions. (2) Signals from regional anthropogenic emissions are much smaller than the concentration changes from atmospheric interannual variability and transportation. Thus, the background fluctuations masking human signals are still a frontier to attribute signal changes to anthropogenic emissions. (3) As the satellite observations operated through a “pinpointing” scanning measure, there is always a trade-off between scope and resolution, as coverage of large emission sources can only be obtained by reducing the temporal resolution restricted by narrow swathes of spaceborne sensors. In other words, achieving frequent revisits or tracking emissions globally and contemporaneously undoubtedly requires a constellation.

Here, we propose a new strategy (Figure 1) that has the potential to be able to monitor global carbon emissions based on the near-real–time emission dataset and the integration, networking, and assimilation of a large number of satellites of different origins. The strategy will first draw a global high spatial–temporal resolution emission map based on near-real–time data and then allow satellites to target by scanning the large emitter. Finally, with more and more data and satellites available, such space CO2 monitoring systems will achieve the coverage, resolution, and timeliness that are required for concrete global emission monitoring. The strategy is compromised of three components.

**DRAWING THE NEAR-REAL–TIME GLOBAL EMISSION MAP**

The current challenge to coupling the “bottom-up” emission inventory with “top-down” satellite observation is that the inventory cannot match the observation in both the spatial and temporal dimensions.4 The inventory usually lacks high temporal resolution, with only annual or monthly data available, and has a time lag of at least 1 year. Recent progress on the emission estimates based on near-real–time human activities data (smart meters, grid data, transportation mobility, etc.) provides opportunities to advance the emission estimates into near real time.5–8 By using geographic information signals, grid data, or in situ observations (e.g., NOx) as CO2 emission proxies, near-real–time daily CO2 emission maps can be developed6 to serve as prior information to facilitate the detection of potential point-source emitters and validation of satellite observations.7 The near-real–time global emission maps display high-resolution spatial information on carbon emissions anywhere and anytime when satellites visit (daily scale), thus providing a credible baseline map for satellite observations.

**ADVANCING KEY POINT-SOURCE MONITORING BY SATELLITE**

Key point emission sources (cities, power plants, etc.) are the main source of anthropogenic carbon emissions (e.g., cities contribute 70% of anthropogenic emissions). With the near-real–time global emission map being constructed, the satellites could now only target huge emitters like cities and plants. This will help keep satellites’ advantages on their high resolution and timeliness without overwhelming the whole emission coverage. For example, the TROPospheric Monitoring Instrument with km-level spatial resolution is adequate for detecting extreme methane leakage from accidental blowouts and methane ultra-emitters.1 Such satellites measure radiiances in the spectral bands (both visible bands and near-infrared bands) and detect carbon dioxide concentrations based on molecular absorption spectra. In combination with other information (ground observations, meteorological data, etc.), atmospheric inversion models can convert the observed CO2 concentration values over the key point sources back to the original concentration field and estimate their carbon emissions. For example, current studies that used Gaussian plume model and OCO-2/3 XCO2 retrievals to estimate corresponding cross-sectional CO2 fluxes from large emission sources showed broad consistency between satellite-based results and emission inventories.9 Continuously and accurately tracking emissions on large emission sources could provide a solid basis for large-scale satellite constellation observations.

Future developments can be made in several aspects. (1) Satellites with diverse attributes can work together to meet different requirements by combining satellites with multiple spatial and spectral resolutions to track plumes at different scales. For global observation, satellites such as GOSAT with sparse but global coverage, a 3-day revisit period, and a continuous data stream target global observations. As for point-source observation, GHGSat with high sensitivity but spatial coverage limit or multispectral instruments such as Sentinel-2 and WorldView-3 with the high spatial resolution is capable of factory-level monitoring. (2) With more advanced satellite missions and their more sensitive instruments to observe XCO2 and XCH4 continuously, like the Geostationary Carbon Cycle Observatory, Carbon Mapper, GHGSat, and the Copernicus Carbon Dioxide Monitoring, specific goals like wide swath, high spatial resolution, frequent revisit, and high accuracy can be anticipated. (3) Artificial intelligence and machine-learning methods can help dig into information that is not directly reflected in satellite imagery. For example, machine-learning methods have been used to automatically enhance the signals of CO2 measurements by satellites, improving the accuracy of inversion results,10 or identifies the operation of factories to track the operational status and emissions of these key point sources.

**GLOBAL SATELLITE NETWORKING**

The satellite constellation is a growing tendency for coming missions that will keep improving the monitoring through the increase in satellite numbers and technologies. Combine all available satellite observations to improve the spatial and temporal accuracy of near-real–time global emission map and assimilation models could help to finally realize global carbon emission monitoring.

An integrated observing system is essential to space-based measurements. Following the roadmap of the Committee on Earth Observation Satellites11 for integrating surface and airborne measurements to support the global stocktake,
several carbon monitoring systems have been proposed, such as the CoCO2 project with the Copernicus Program (https://coco2-project.eu/, European Union) and the NASA Carbon Monitoring System (https://carbon.nasa.gov/, the USA), to accelerate the integration of multiple observation sources and to provide verifiable and transparent data products.

Given the large-scale data generated by satellites and integrated observing systems, standardization and sustainable reusing of observations are guaranteed for more efficient data use. The Copernicus Climate Change Service (https://climate.copernicus.eu/) has provided a landmark example of large-scale climate data sharing for a global data-exchange strategy and climate services. A free and open data-sharing platform led by governments will help break down the current data barriers caused by the monopoly of different stakeholders. Cloud-based platforms provide large-scale storage and supercomputing power, such as the Copernicus Climate Data Store toolbox (https://cds.climate.copernicus.eu/) or Google Earth Engine (https://code.earthengine.google.com/). The cloud-based platforms are needed to pool more available observation data and improve the computing power of the earth system modeling and inversion and assimilation system, to increase the spatial resolution from the current 0.1° × 0.1° to the kilometer level, and to shorten the temporal interval from annually to monthly or daily.

CONCLUDING REMARKS

Human activity data-based emission inventory can provide a sector-specific, systematic dataset that is comparable between countries, while satellite observations can support independent, low-cost, spatially distributed, and directly observed datasets, which are especially beneficial for areas that lack bottom-up data. Combining the superiorities of the near-real-time dataset and the satellite observations, an innovative technical route is proposed for transitioning from inventory-based carbon monitoring to satellite-driven carbon monitoring and from point-source carbon monitoring to the global scale. A near-real-time carbon map primarily derived from emission inventory with poor resolution in local areas can provide prior information for satellite observations and constrain satellite retrievals. Continuous point-source monitoring by satellites, in turn, can improve accuracy to form a dual-update mechanism with a long-term goal of quantifying anthropogenic emissions by satellite constellation only as an independent method. Based on this mechanism, gathering in-orbit and soon-to-be-launched satellites into a comprehensive observing network allows us to widen the monitoring space from a key point to a unified globe, jointly contributing to the data foundation for implementing international climate treaties and climate policies, and finally pave the way to a more accurate and transparent global stocktake.

REFERENCES

1. Crisp, D., Dolman, H., Tanhua, T., et al. (2022). How well do we understand the land-ocean-atmosphere carbon cycle? Rev. Geophys. 60, e2021RG000736.
2. Deng, Z., Ciais, P., Tzompa-Sosa, Z.A., et al. (2022). Comparing national greenhouse gas budgets reported in UNFCCC inventories against atmospheric inversions. Earth Syst. Sci. Data 14, 1639–1675.
3. Liu, Z., Ciais, P., Deng, Z., et al. (2020). Near-real-time monitoring of global CO2 emissions reveals the effects of the COVID-19 pandemic. Nat. Commun. 11, 6292.
4. Liu, Z., Deng, Z., Zhu, B., et al. (2022). Global patterns of daily CO2 emissions reductions in the first year of COVID-19. Nat. Geosci. 15, 615–620.
5. Liu, Z., Sun, T., Yu, Y., et al. (2022). Near-real-time carbon emission accounting technology toward carbon neutrality. Engineering.
6. Dou, X., Wang, Y., Ciais, P., et al. (2022). Near-real-time global gridded daily CO2 emissions. Innovation 3, 100182.
7. Weir, B., Crisp, D., O’Dell, C.W., et al. (2021). Regional impacts of COVID-19 on carbon dioxide detected worldwide from space. Sci. Adv. 7, eabf9415.

Figure 1. Framework of the carbon-monitoring strategy
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DECLARATION OF INTERESTS
The authors declare no competing interests.