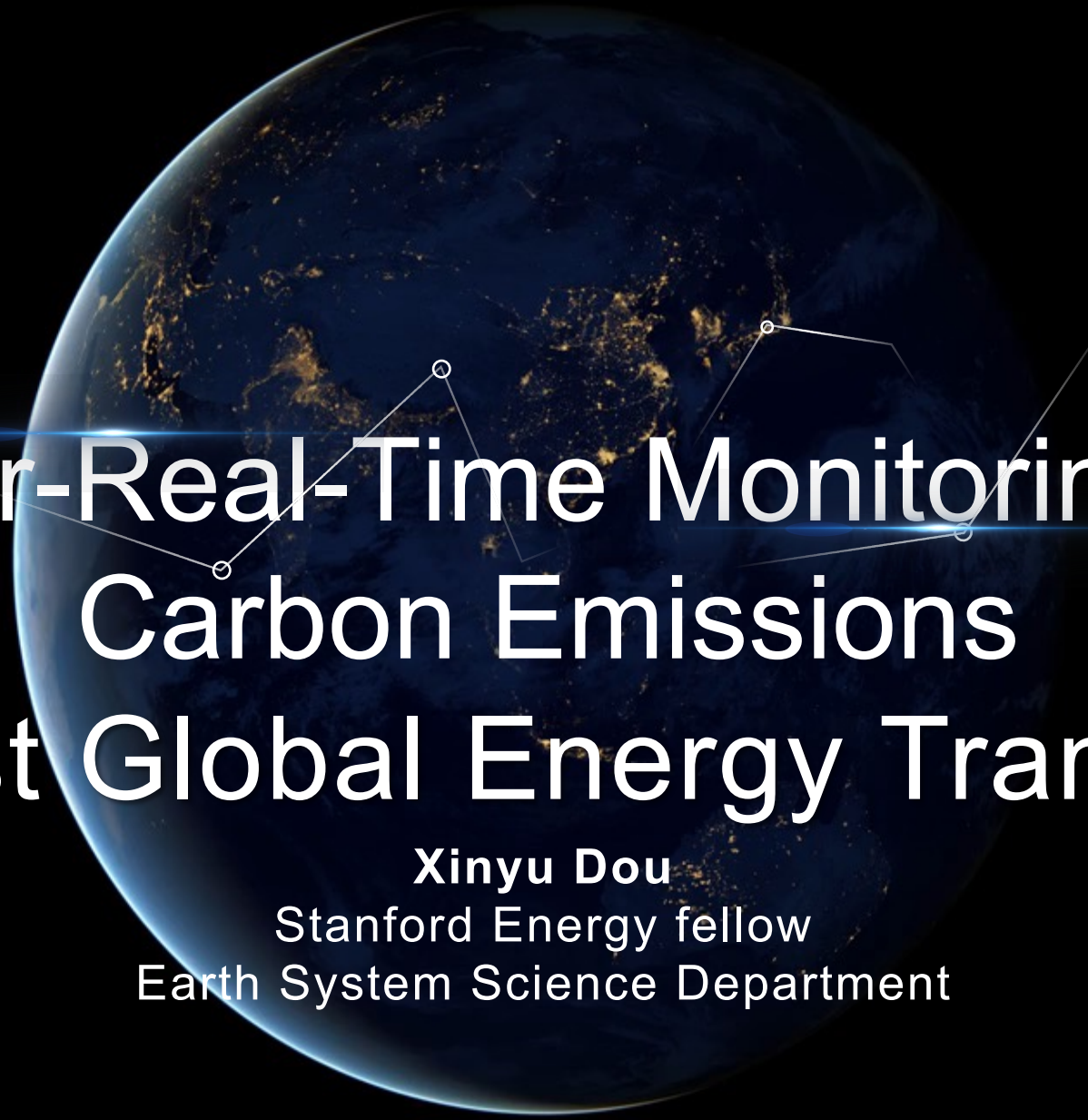


Near-Real-Time Monitoring of Carbon Emissions amidst Global Energy Transition

Xinyu Dou
Stanford Energy fellow
Earth System Science Department


Greenhouse gases

Background

Since the industrial era began around 1850,
anthropogenic greenhouse gases are estimated to have contributed around +1.5°C of warming.

CO_2
CARBON DIOXIDE

The primary greenhouse gas, responsible for about three-quarters of emissions

+0.8ºC

CH_4
METHANE

Accounts for about 16% of all greenhouse gas emissions

+0.5ºC

Others

Accounts for only 6% of all greenhouse gas emissions

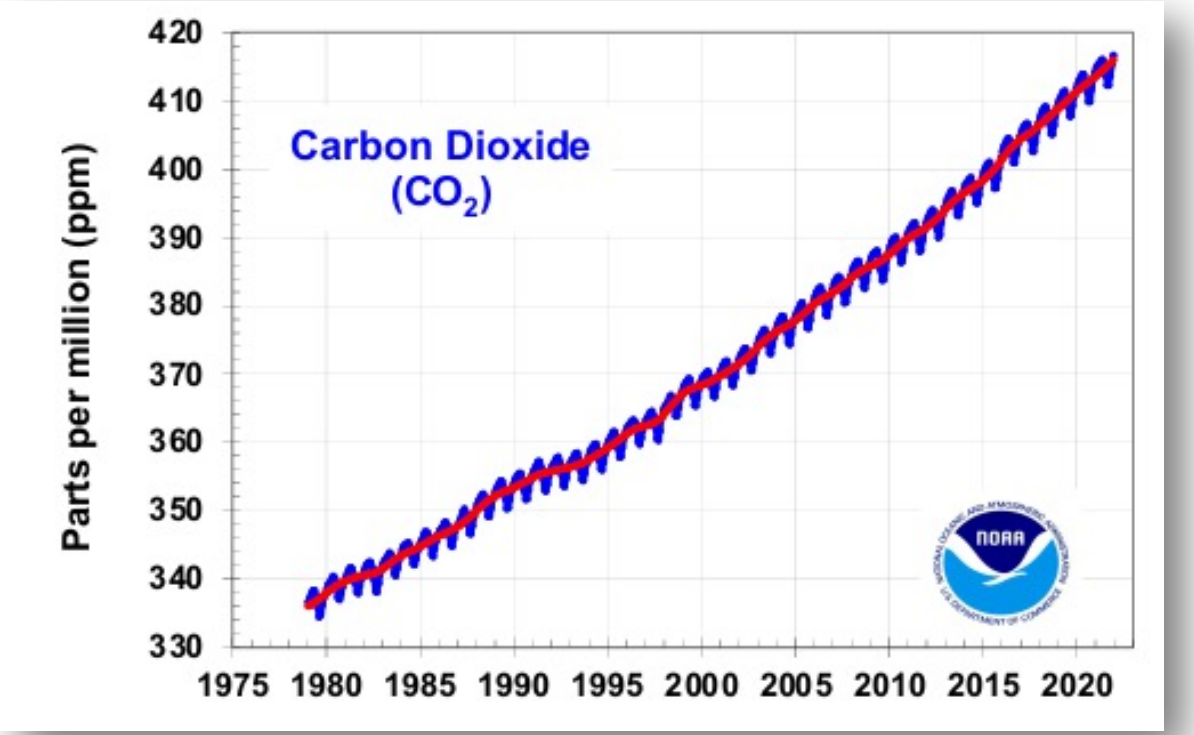
+0.2ºC

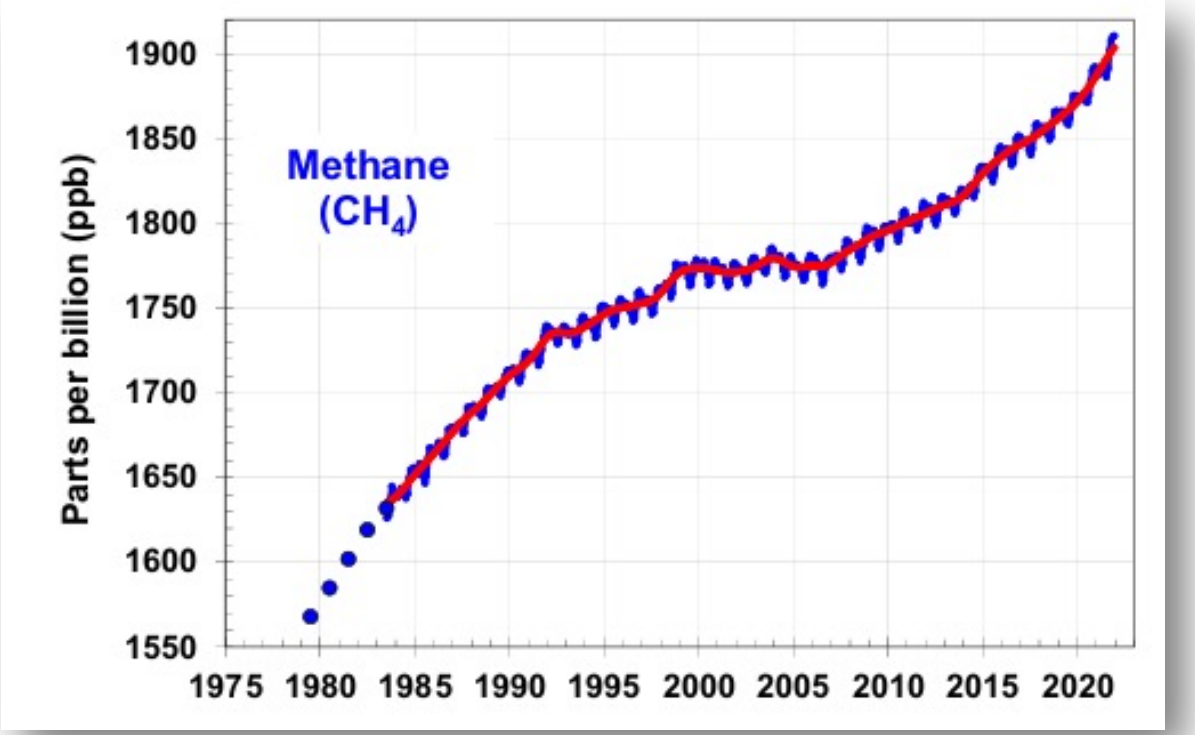
(IPCC)

Among all greenhouse gases, CO_2 and CH_4 contribute the most to global warming.

Background

Atmospheric levels of CO_2 and CH_4 have been rising in recent decades

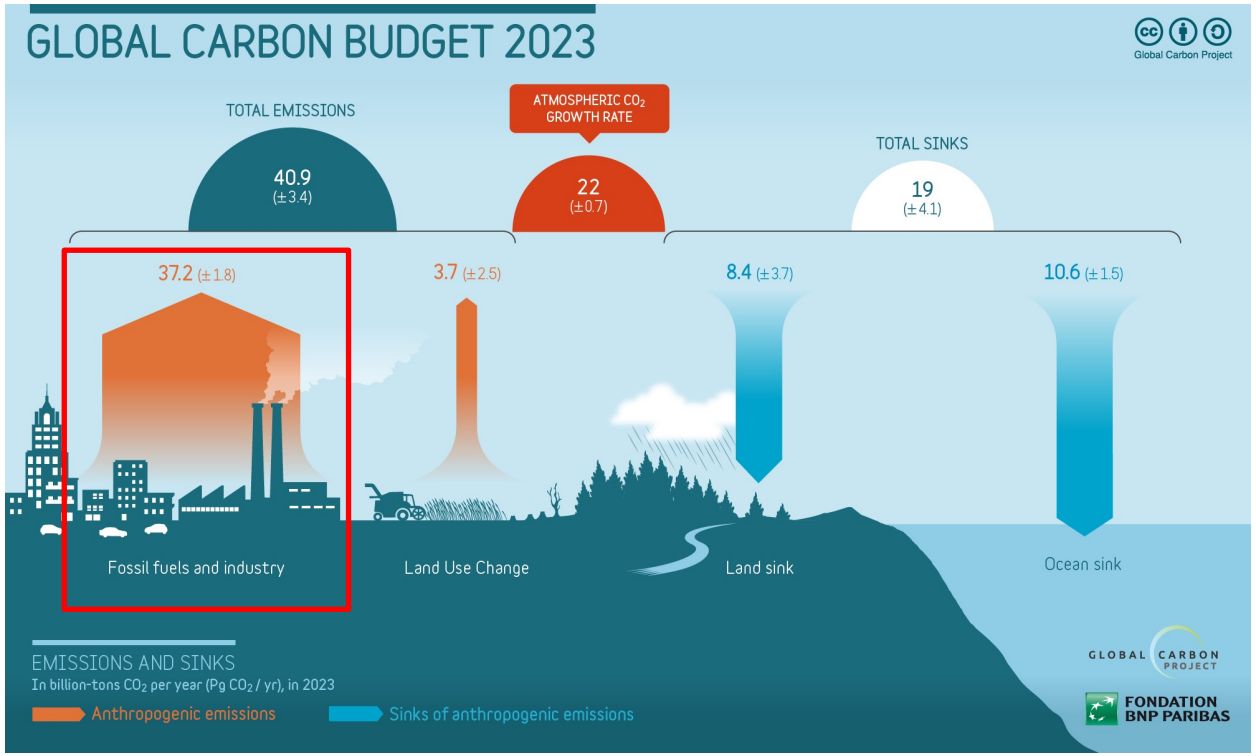




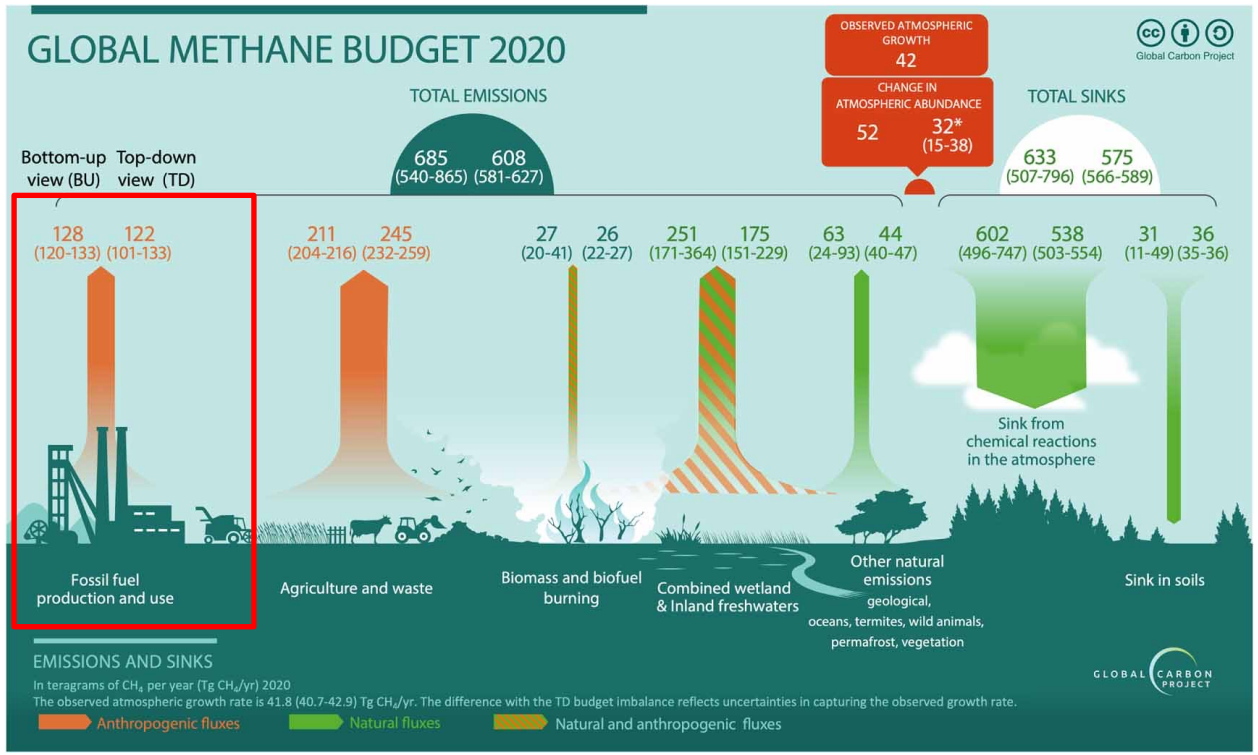
The NOAA Global Greenhouse Gas Reference Network (GGGRN),

Background

Emissions caused by human activities are the main reasons for the increase of concentration in the atmosphere.



(Pierre Friedlingstein, …, **Xinyu Dou**, et al. Global Carbon Budget 2024)



(R B Jackson, et al. Global Methane Budget 2000-2020)

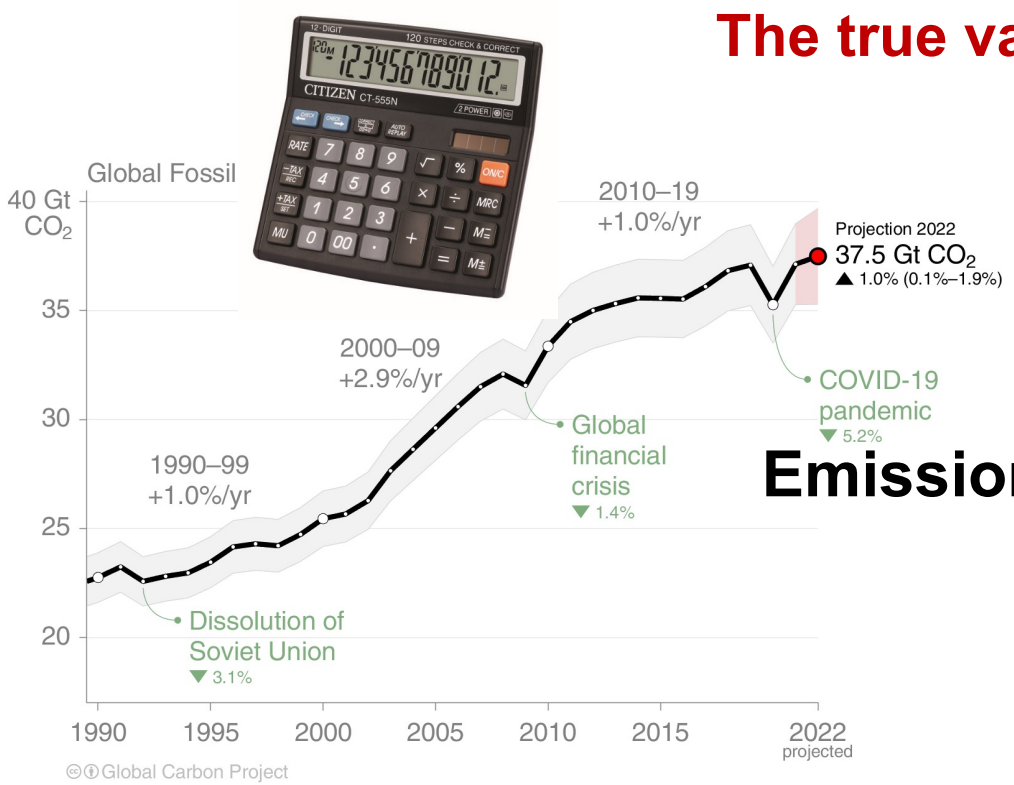
Accurately quantifying fossil emissions is important

CO_2: emissions from fossil fuels consumption **CH_4: emissions from fossil fuels production and transportation**

Background

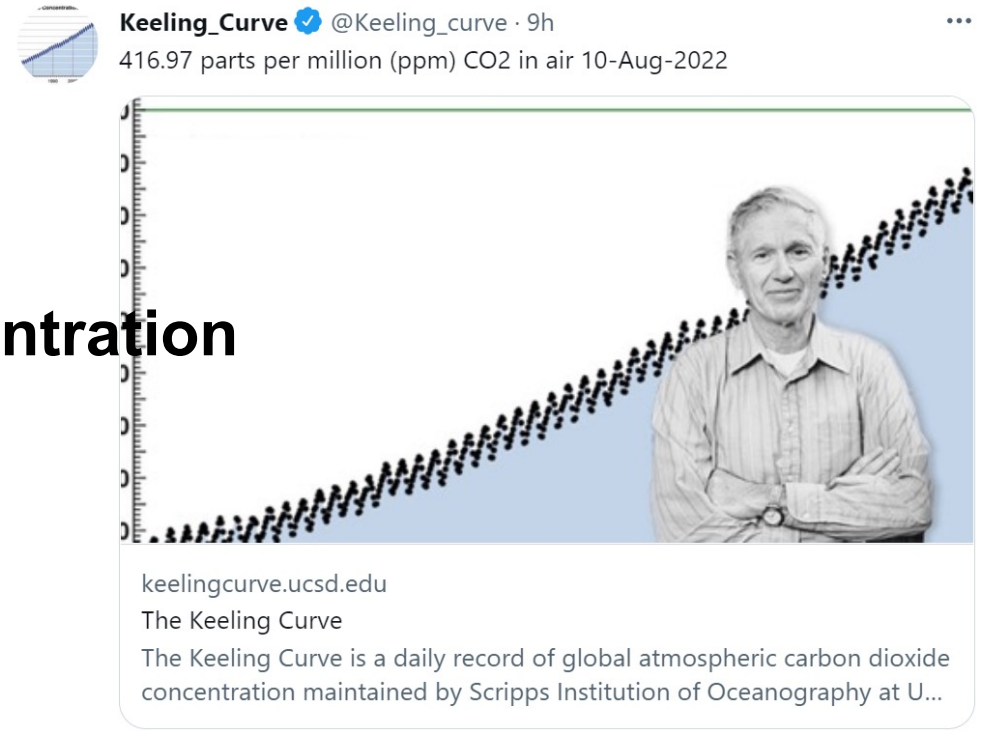
Core scientific issues:

The true value of carbon emissions?



(Friedlingstein et al. Global Carbon Project 2022)

Emission ⟷ **Concentration**



The quantification of carbon emissions requires the integration of investigation, measurement, simulation, statistics and other aspects.

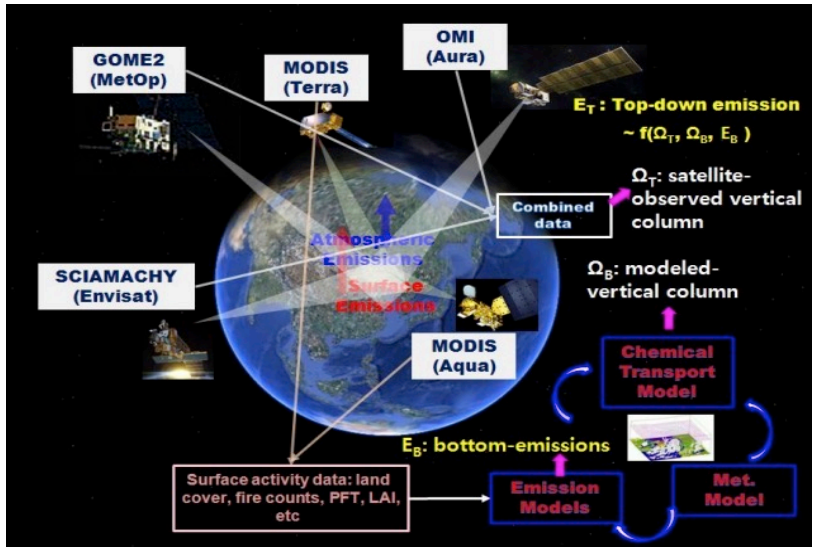
Background

Two quantification methods of carbon emissions

(1) "Top-Down" Emission Inversion

Emissions → $E = \alpha \times \Omega$

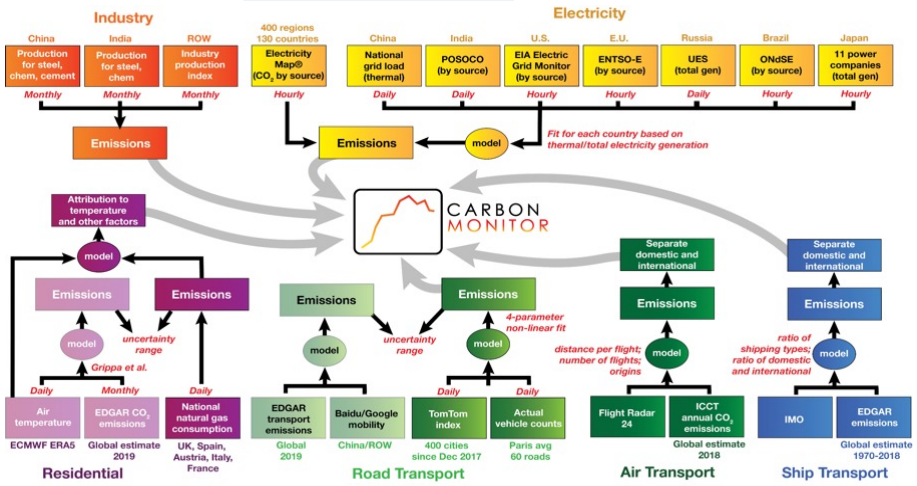
Observations	Functional relationships between observations and emissions
Surface Aircraft Satellite	Empirical methods Atmospheric chemistry models Inversion models



(2) "Bottom-Up" Emission Inventory Modeling

Emissions = $E = AD \times EF$

Activity Data	Emission factor
Relevant statistical data for various sectors	Material balance On-site testing Model calculations



(Zhu Liu, …, **Xinyu Dou** et al., 2020)

Background

Carbon Emissions: Science, Technology and Policy Intersection

Demand for timely data: policy response / status assessment / scenario prediction

Dangerous driving for all humans: actions and policies rely on historical data rather than current (real-time) data

Background

Research Ideas-Timeliness, completeness, and precision

"Read the newspaper"

Historical data analysis

Lag of one year or more

Based on historical statistics

"Live"

Near-real-time analysis

Lag of only one month

Satellite remote sensing, computers, web technologies, increased frequency of data acquisition, processing and distribution

"Be there"

Real-time analysis

No time lag

Restricted by current observation and calculation technology, it is difficult to achieve real-time

Innovative research paradigms: near-real-time quantitative methods to characterize real-time activity, near-real-time data to approximate real-time change

Fossil CO_2 Emissions

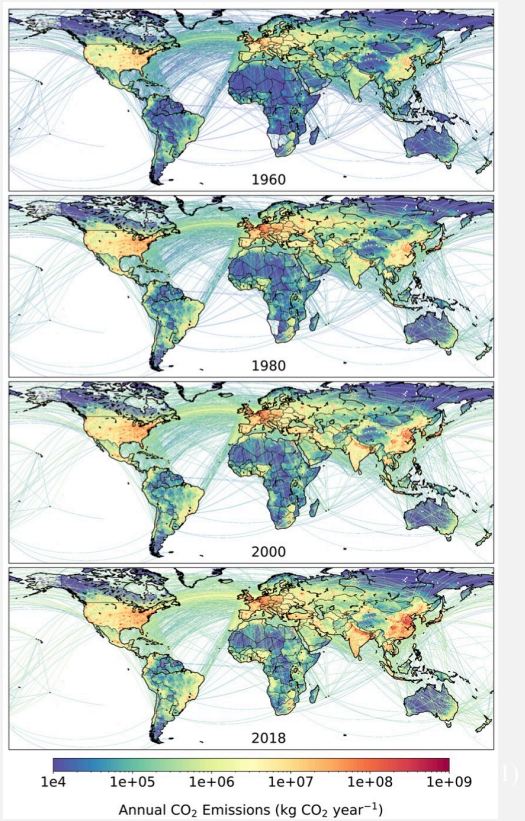
Background

Accurate and timely fossil emission data is an important basic data for climate change assessment

Time Lag → **Near-real-time ?**

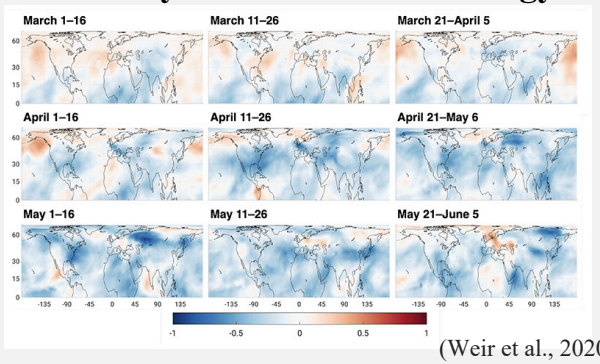
Annual → **Daily ?**

Lagging behind in emissions for multiple years



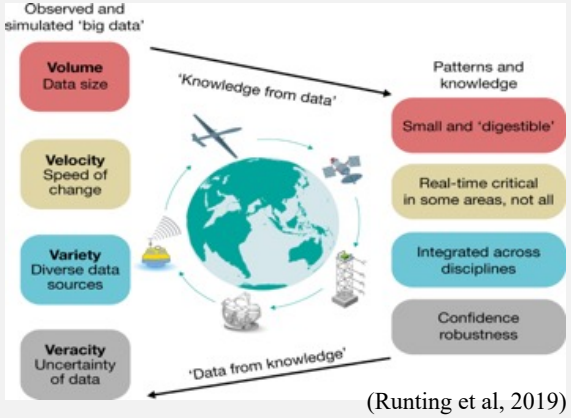
(Matthew W. Jones et al., 2021)

Satellite remote sensing timely observation technology



(Weir et al., 2020)

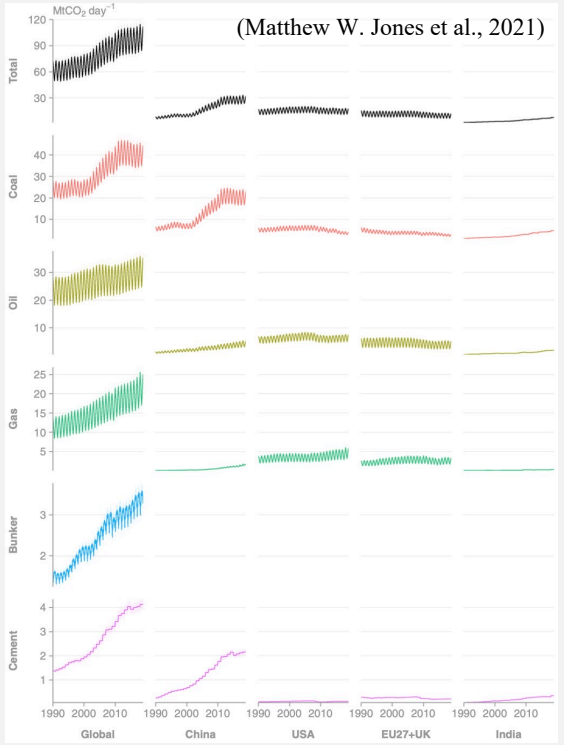
Multi-source multi-dimensional big data



(Runting et al, 2019)

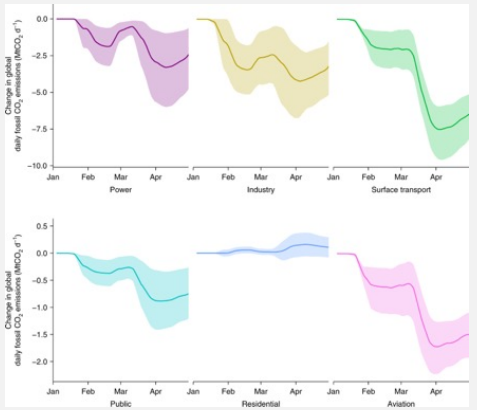
Annual or monthly

Monthly fossil CO_2 emissions

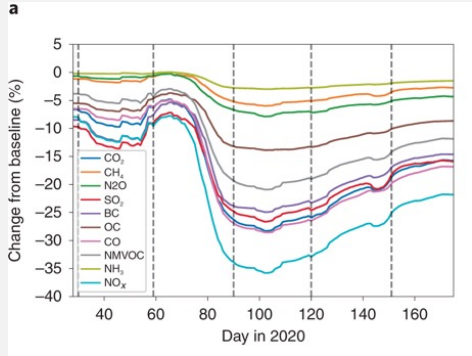


Time series of monthly CO_2 emissions as estimated by GCP-GridFEDv2019.1. for the period 1990–2018 (Mt CO2 day−1).

Carbon emission estimation based on daily proxy data



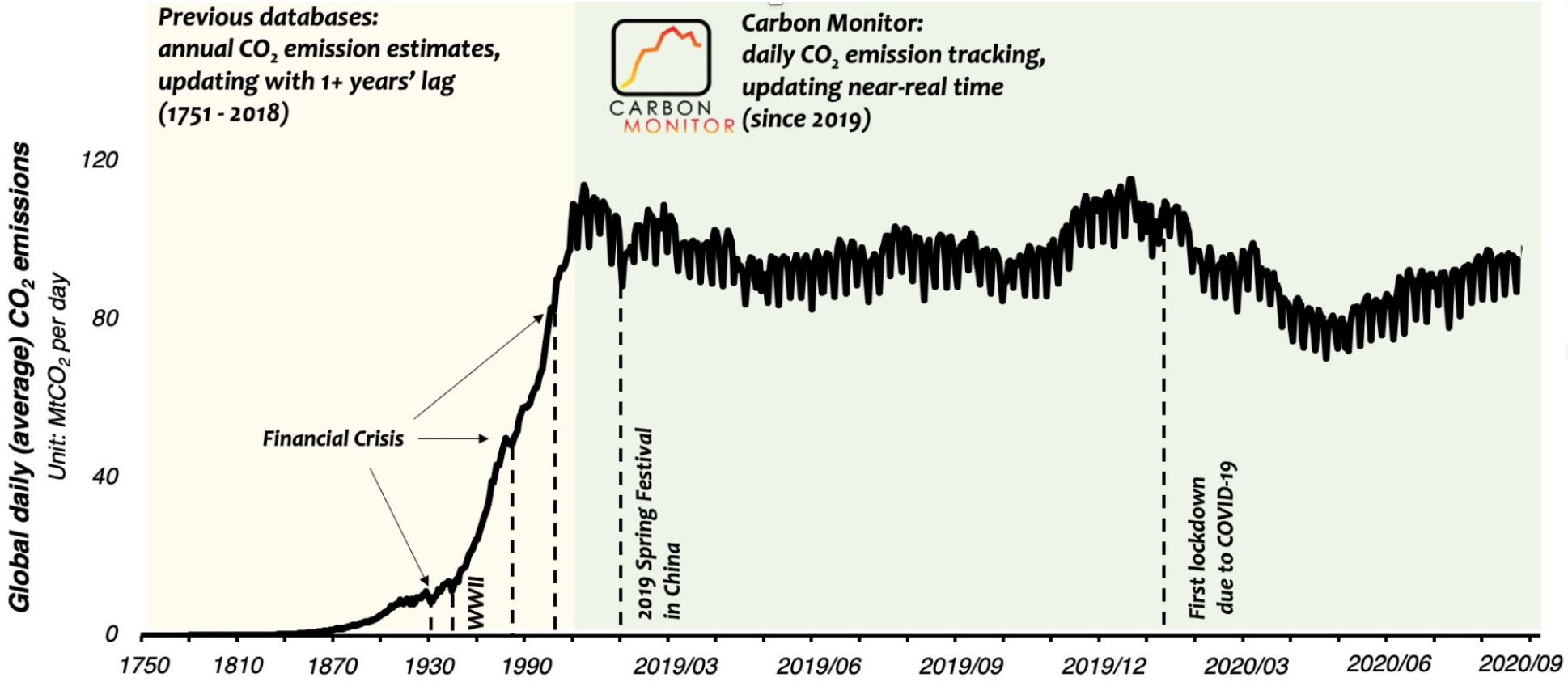
(Le Quéré et al, 2020)



(Forster et al, 2020)

Data and methods

- **1. Near-real-time national-level emissions inventory**



Timeliness

From the original **lag of more than one year** to **near-real-time**

Resolution

From the original **annual** change to the **daily** resolution

(Zhu Liu, …, **Xinyu Dou**, et al, *Nature Communications 2020*;
Zhu Liu, …, **Xinyu Dou**, et al, *Scientific Data 2020)*

Data and methods

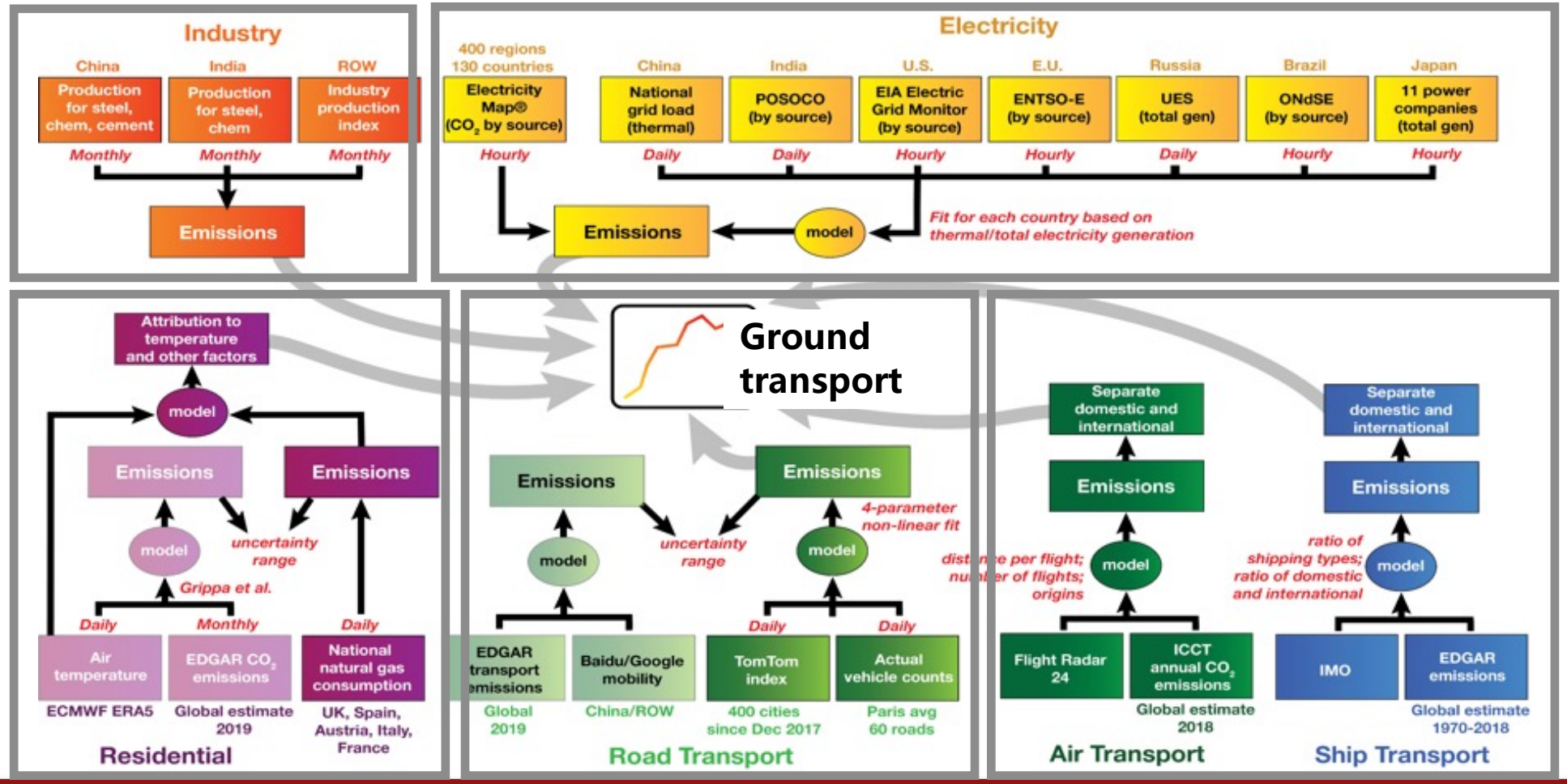
Emission source
Sector

Location
Positioning

Degree
Amount

Dynamic
Spatiotemporal change

Industry

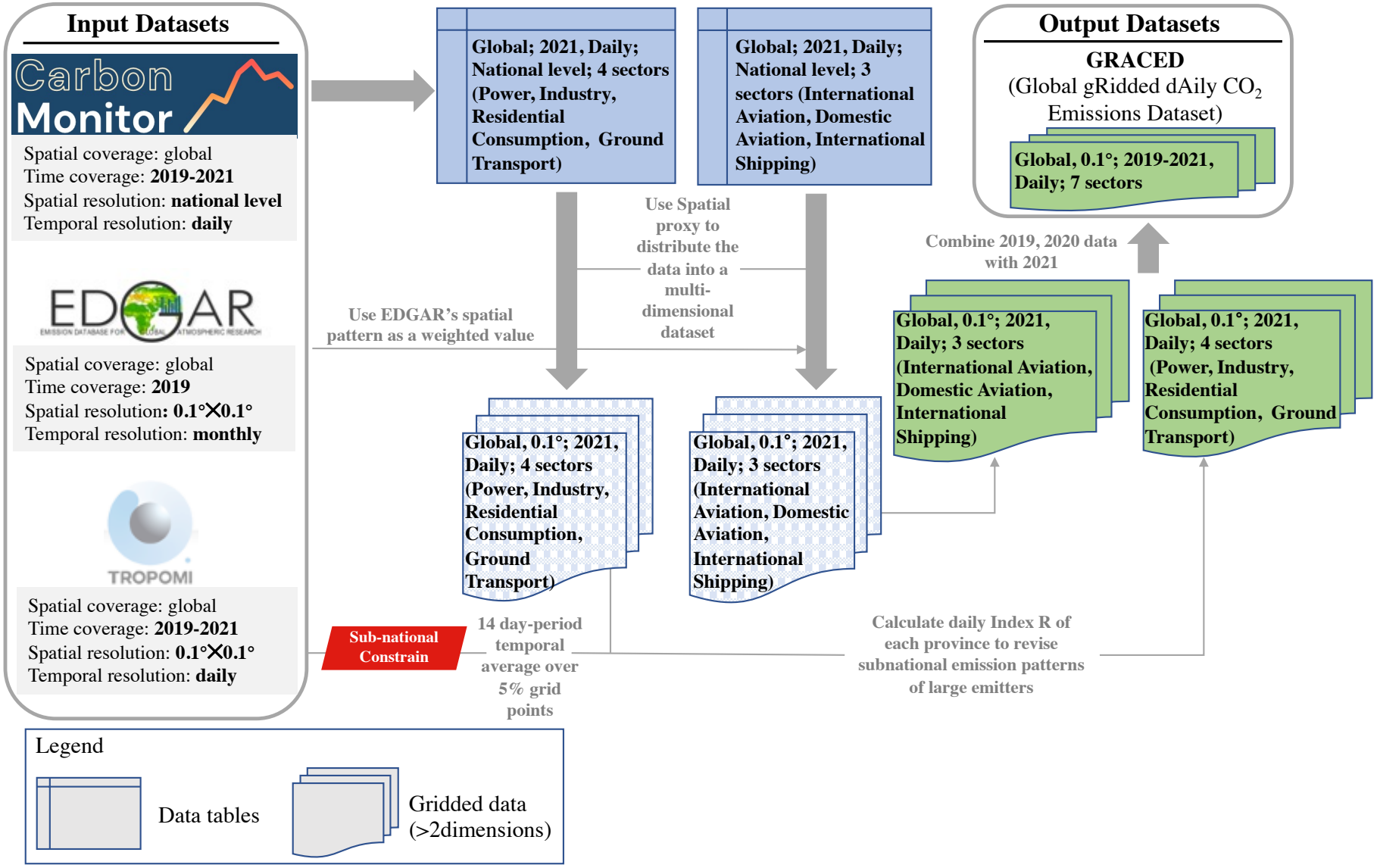


Residential consumption

Power

Aviation
Shipping

Data and methods



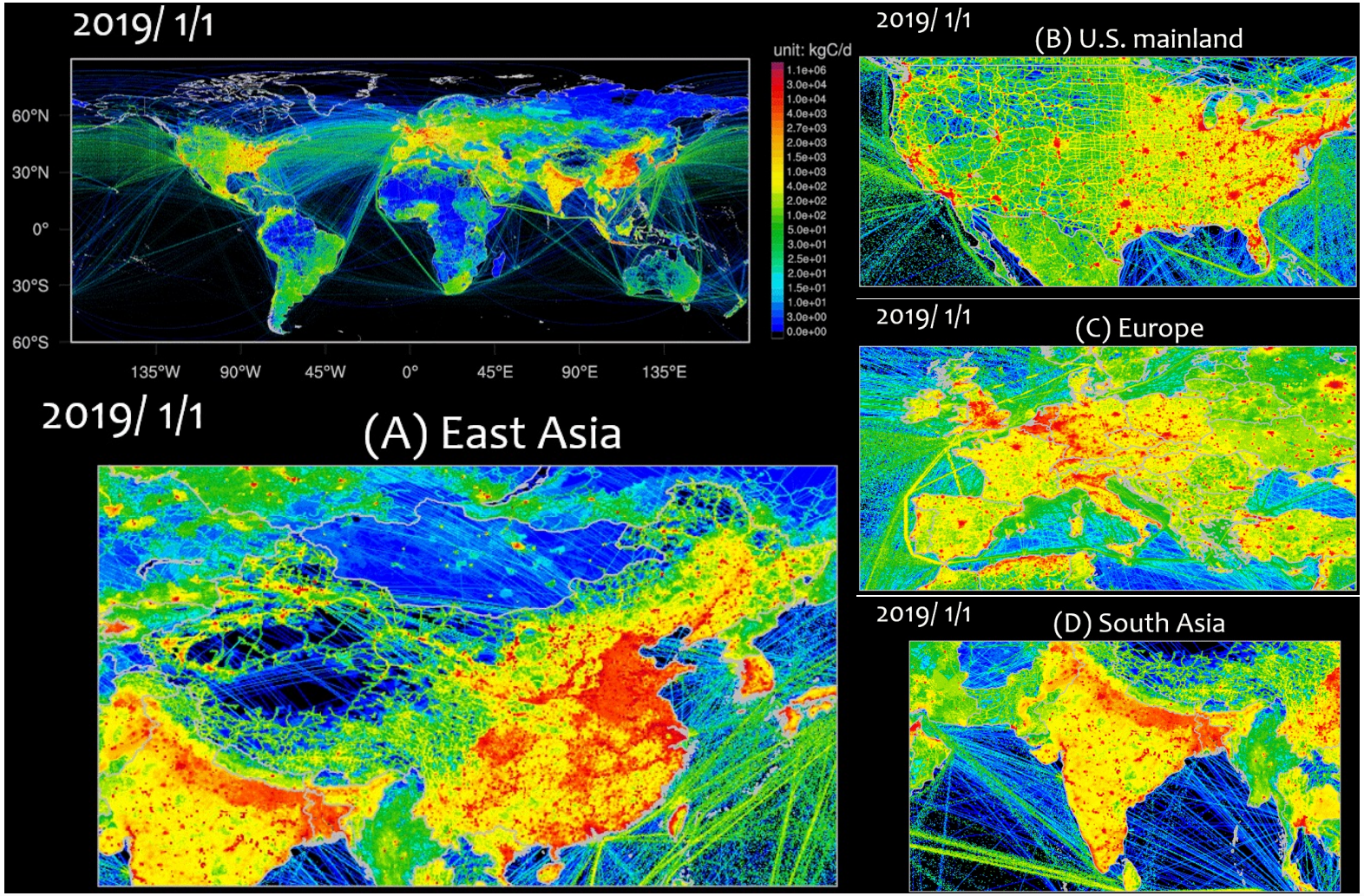
Method Framework

Use geographical patterns supplied by EDGAR, as well as a sub-national proxy according to TROPOMI NO_2 retrievals, in order to distribute Carbon Monitor daily emissions at country-level to our finer grid.

(**Xinyu Dou**, *et al, Scientific Data 2023;* **Xinyu Dou**, et al, *The Innovation 2022)*

Results

- The first **Near-Real-Time Daily CO_2 emissions map**



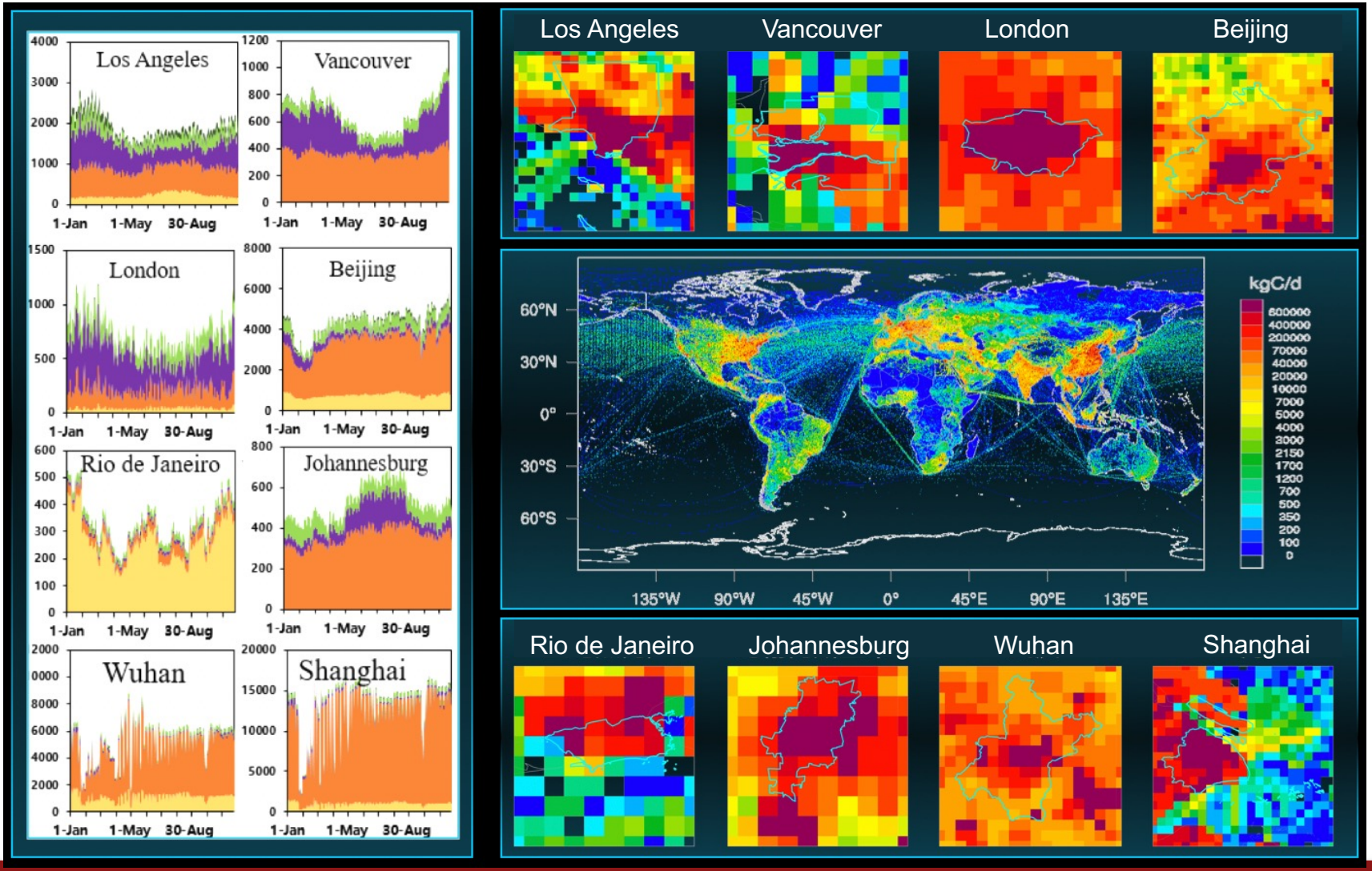
- Fast update in near-real-time;
- The only daily scale global CO_2 emissions map with both high spatial and temporal resolution.

Spatial resolution	Temporal resolution
$0.1° \times 0.1°$	Daily

(**Xinyu Dou**, *et al, Scientific Data 2023;*
Xinyu Dou, et al, *The Innovation 2022)*

Results

- The **near-real-time daily CO_2 emissions map with a spatial resolution of 0.1 °**



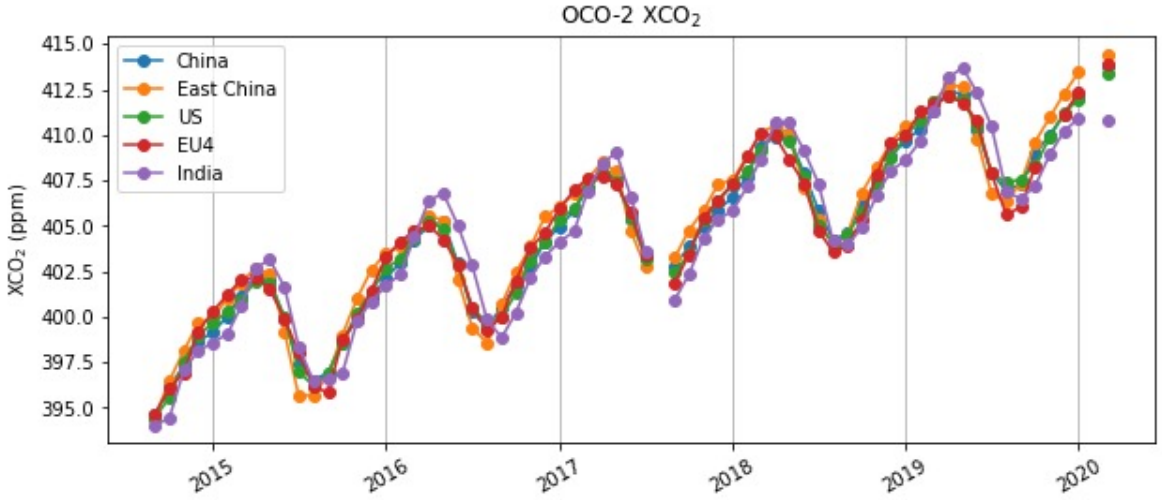
- Focus on the provincial or urban level

Support the scientific and accurate realization of local climate mitigation goals

(**Xinyu Dou**, *et al, Scientific Data 2023;* **Xinyu Dou**, et al, *The Innovation 2022)*

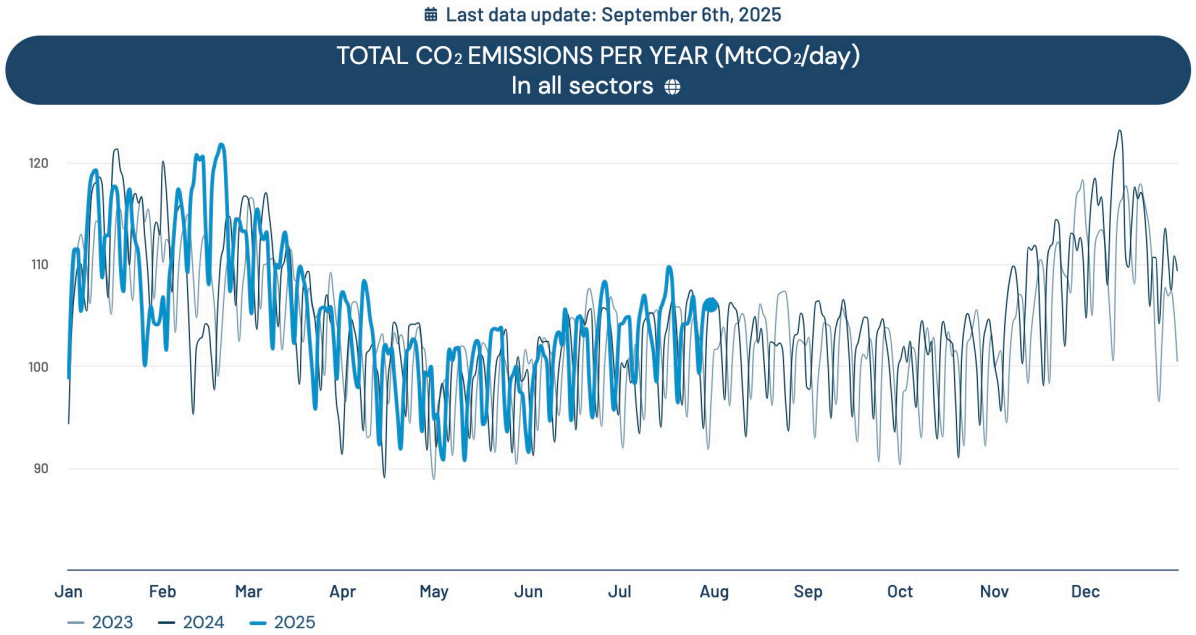
Results

Daily data: reflect the seasonal variation characteristics of anthropogenic carbon emissions



Seasonal variation in carbon dioxide concentration signals

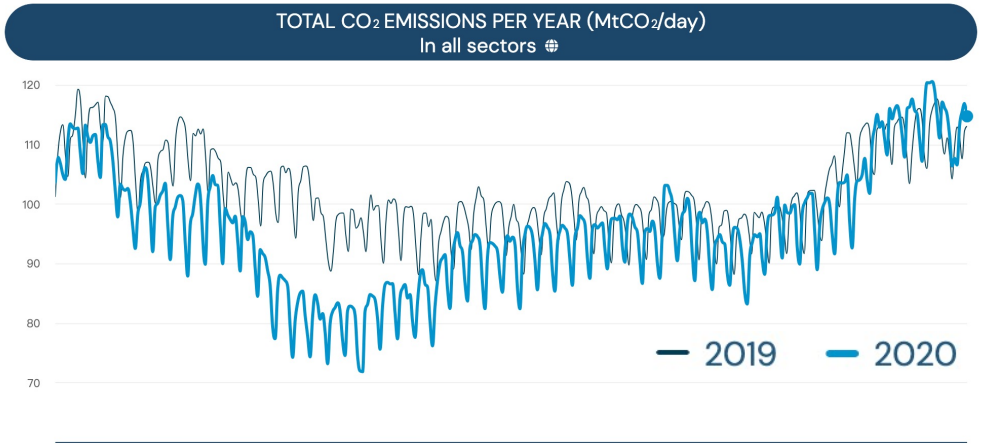
Frederic Chevallier et al., GRL, 2020

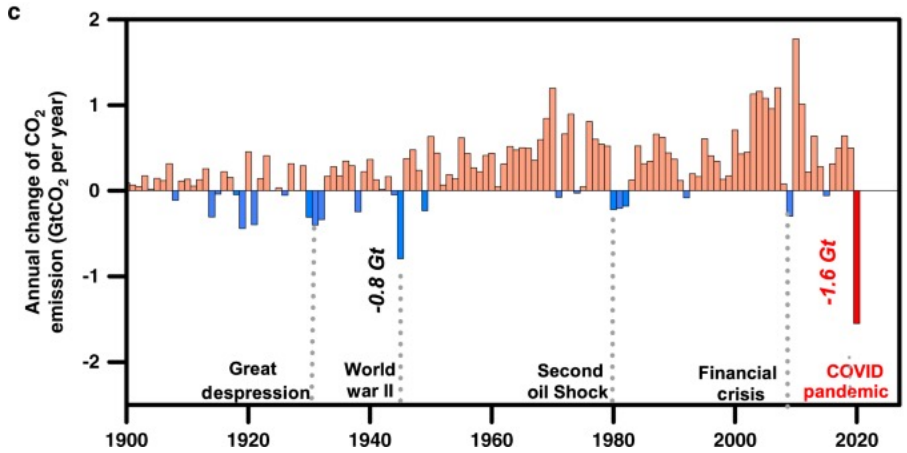


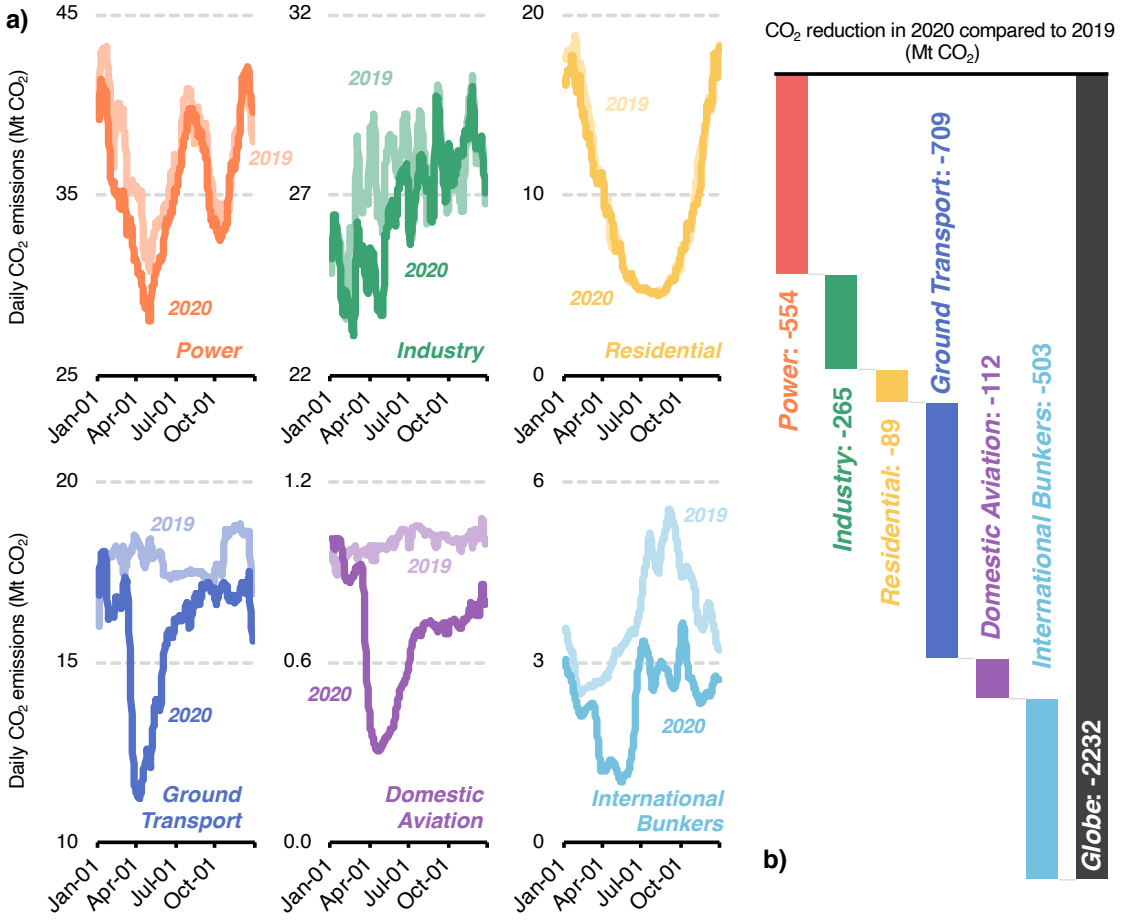
Seasonal variation in carbon emissions

Results

Daily data: reflect the impact of the COVID-19 on carbon emissions from human activities





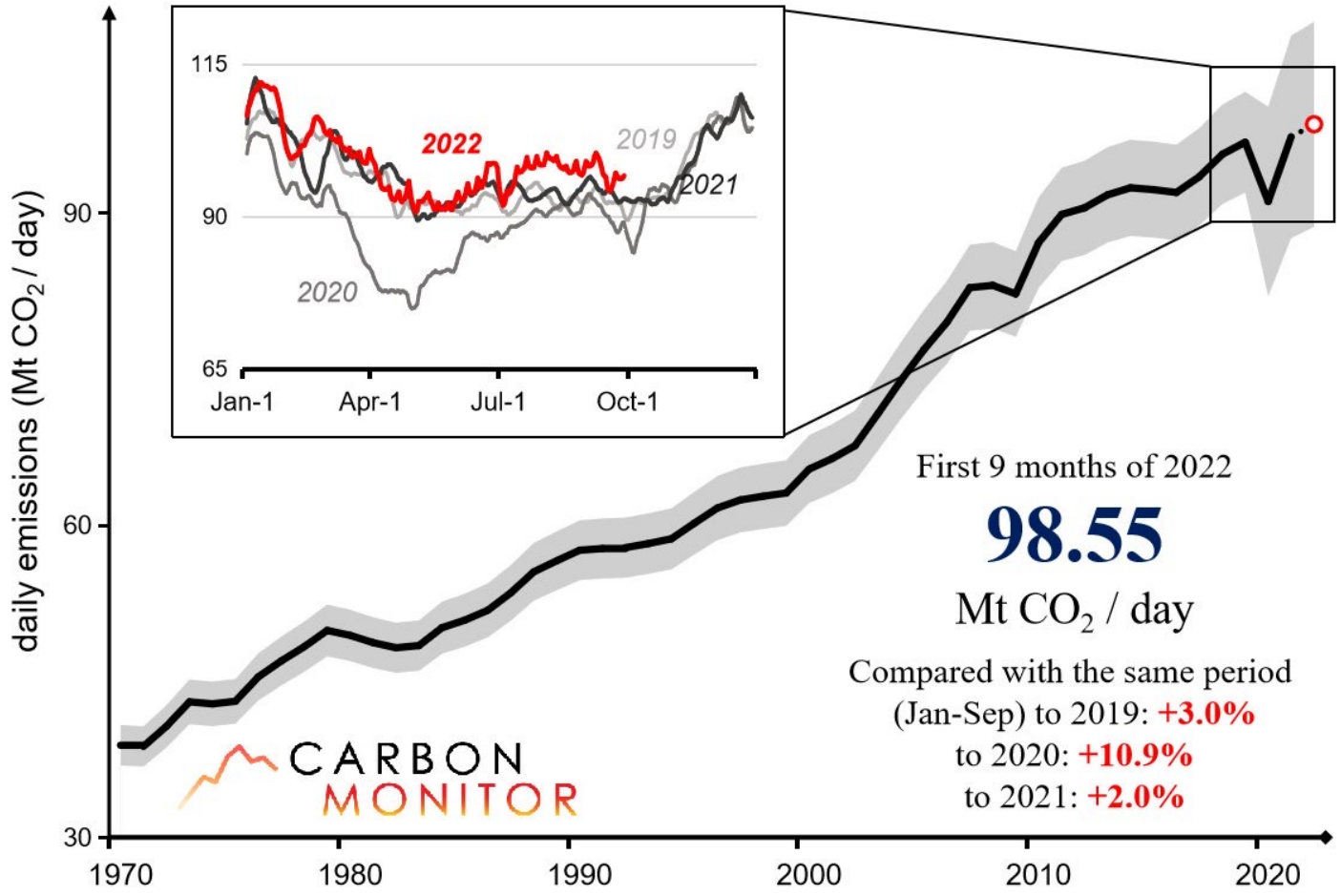


- In 2020, the global carbon emissions **dropped to a record level**;
- **Transport, power, industry** and other sectors have made great contributions to emission reduction.

Zhu Liu, …, Xinyu Dou et al, 2022, *Nature Geoscience*

Results

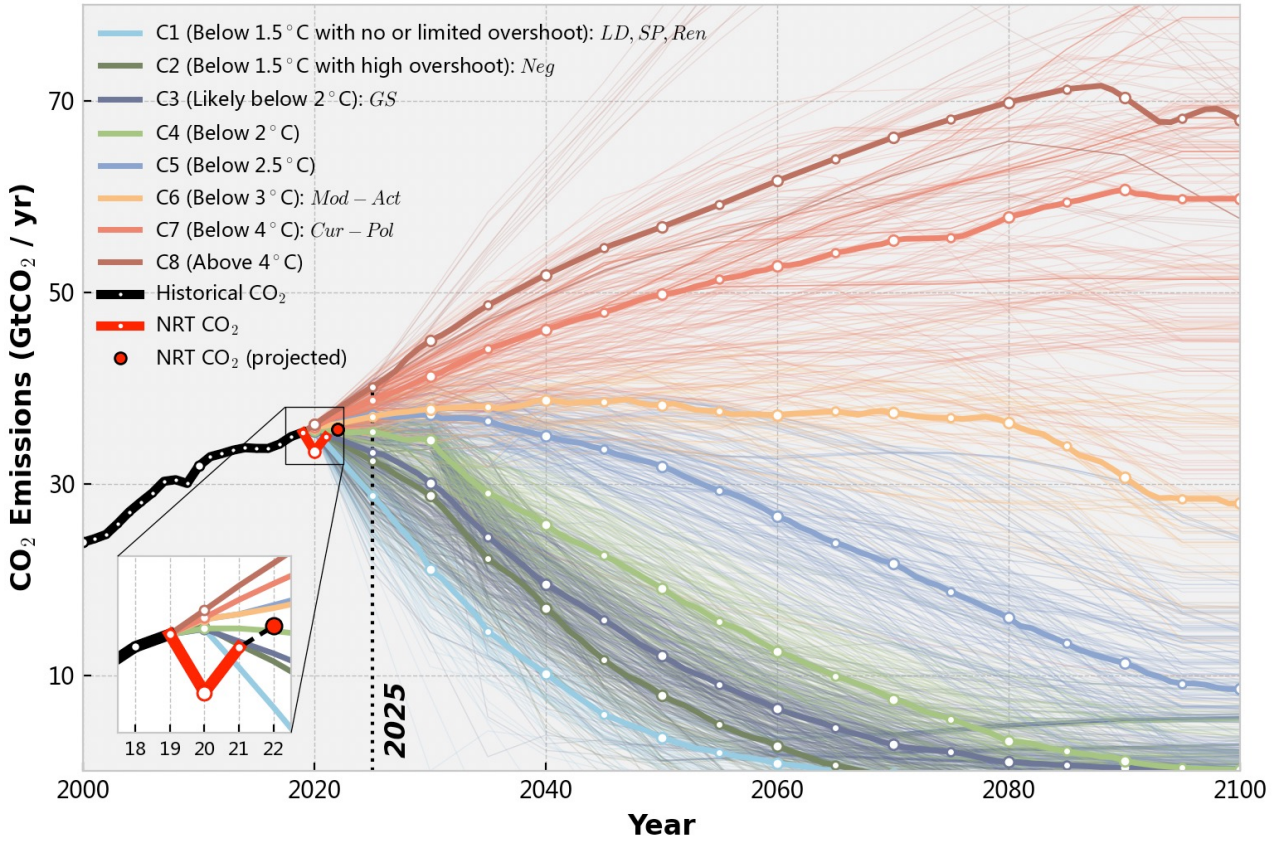
Global failure to achieve a green recovery?



In the first nine months of 2022, the growth rate was 3.0% compared with the same period in 2019, 10.9% compared with the same period in 2020, and 2.0% compared with the same period in 2021.

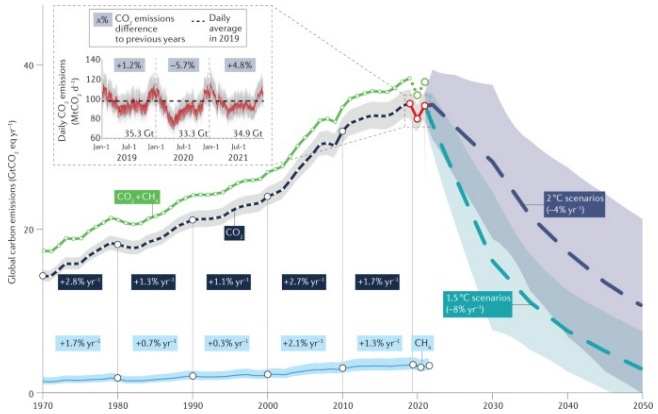
Results

Near-real-time data: the latest changes in anthropogenic carbon emissions are significantly different from the IPCC scenario paths



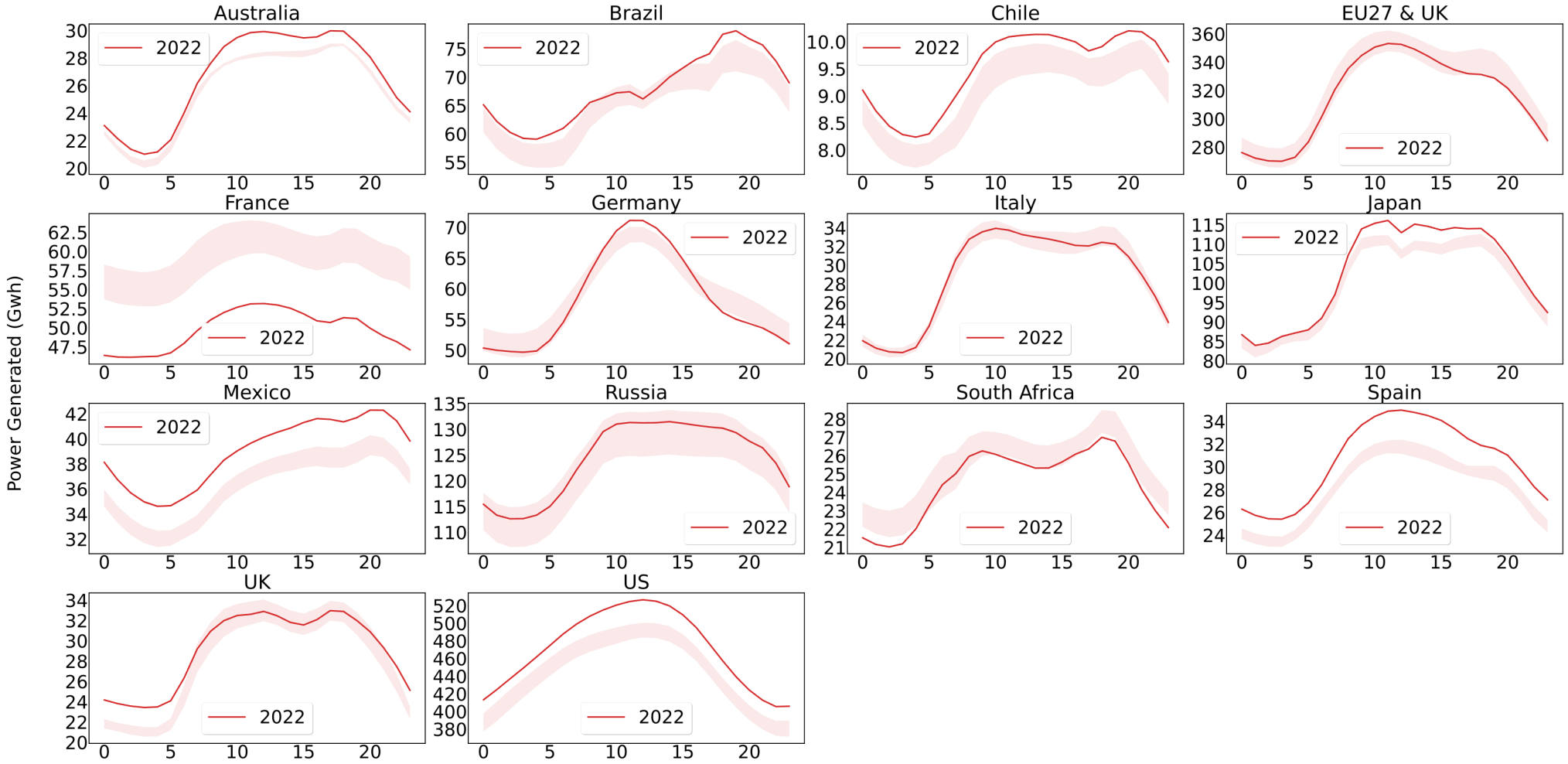
Zhu Liu et al, 2022, *Nat. Rev. Earth Environ.*

- The rapid rebound of carbon emissions in the post-epidemic period is contrary to the scenario of reaching the peak before 2025 under the 1.5 ℃ and 2 ℃ scenarios of IPCC AR6.
- If the current emission level is maintained, the updated 1.5 ℃ global residual carbon budget may be used up in 9.5 years.



Results

Hourly data: accurately reflect the law of energy production in a day



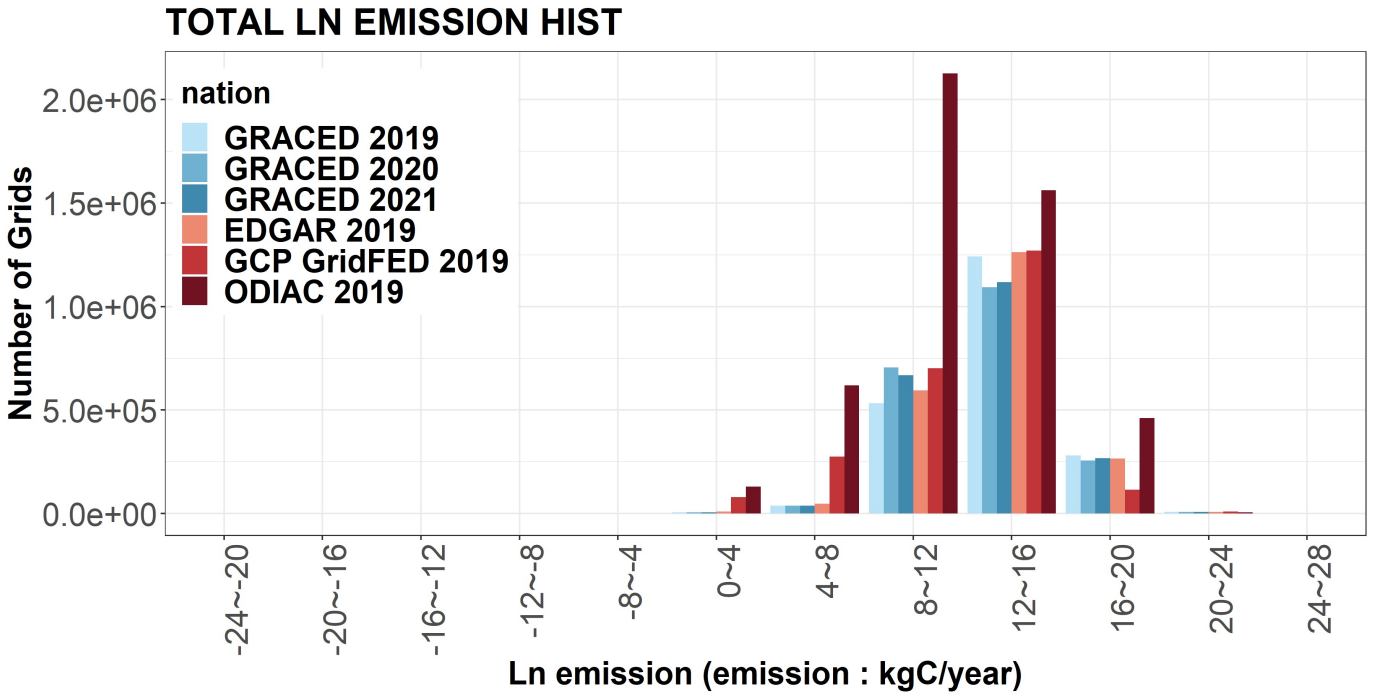
Results

Uncertainty analysis

GRACED	2019	2020	2021
Power	±11.2%	±13.4%	±13.5%
Industry	±18.4%	±33.4%	±33.4%
Residential	±16.1%	±42.0%	±42.0%
Ground transport	±14.1%	±15.5%	±15.5%
Domestic Aviation	±16.1%	±18.6%	±18.6%
International Aviation	±37.1%	±16.0%	±16.0%
International Shipping	±16.7%	±16.7%	±16.7%
Total	±23.1%	±19.9%	±19.9%

The reliability of GRACED was not sacrificed for the sake of higher spatiotemporal resolution that GRACED provides.

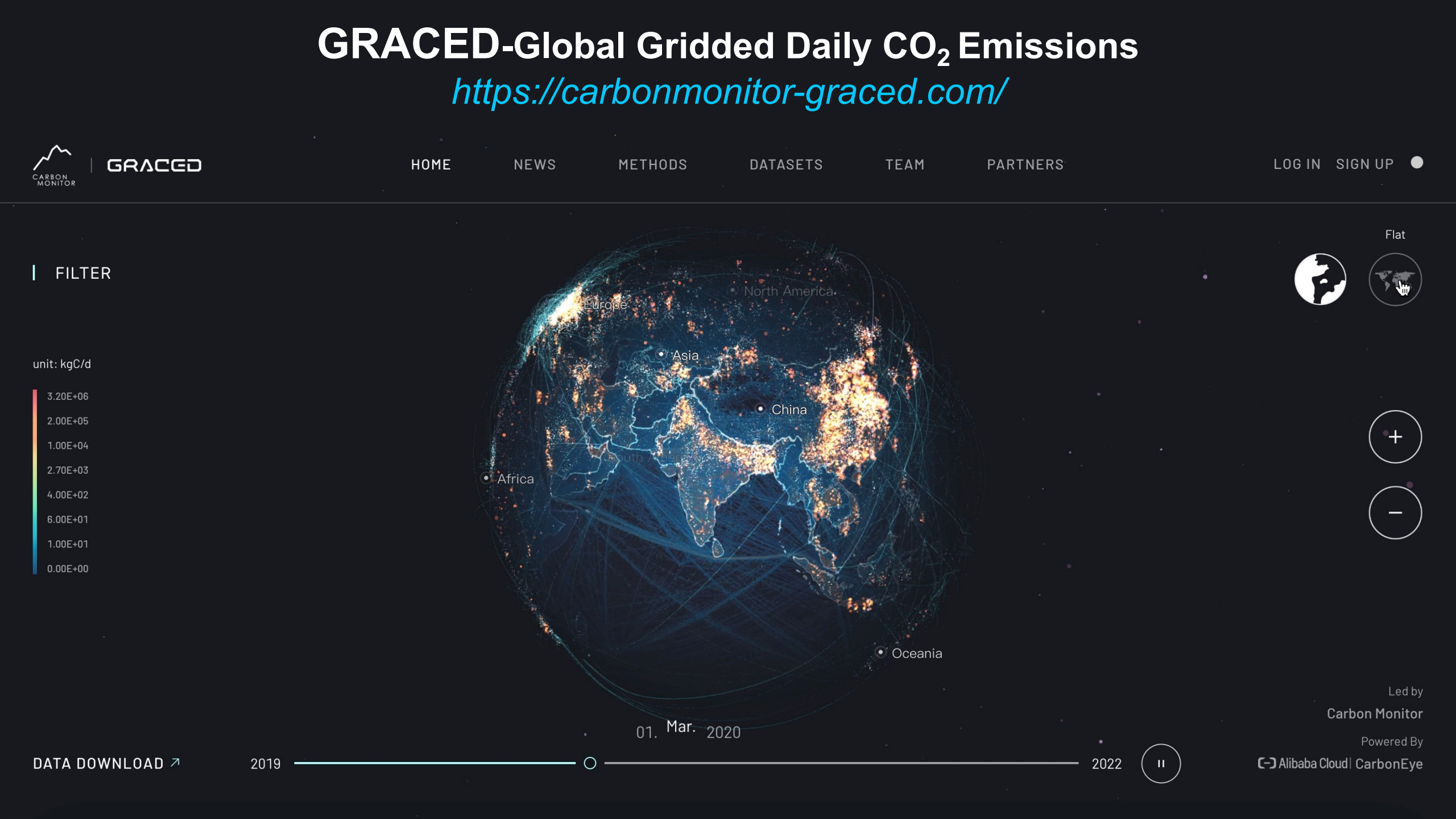
Validation against other datasets



We also examined the distribution of emission in a grid-wise perspective for major emission datasets, GCP-GridFED, ODIAC and EDGAR, and compared it with GRACED. The similarity in emission distribution and the number of non-zero emission grids were observed in GRACED, EDGAR and GCP-GRIDFED.

GRACED-Global Gridded Daily CO_2 Emissions

https://carbonmonitor-graced.com/



GRACED-Global Gridded Daily CO_2 Emissions

https://carbonmonitor-graced.com/

GRACED-Global Gridded 8-Day CH_4 Emissions

https://carbonmonitor-graced.com/

Research achievements

NRT emission accounting dataset: Carbon Monitor

- Carbon Monitor received over **one million** downloads to date.
- Carbon Monitor has been contributed by more than **30 international research institutions**.

Carbon Monitor Datasets:

Grid https://carbonmonitor-graced.com
Global https://carbonmonitor.org
China https://cn.carbonmonitor.org/
Europe https://eu.carbonmonitor.org/
US https://us.carbonmonitor.org/
Cities https://cities.carbonmonitor.org/
Power sector https://power.carbonmonitor.org/

References

Real-time monitoring of global carbon emissions reflects the impact of the COVID-19(***Nature Communications***) :

https://www.nature.com/articles/s41467-020-18922-7

Introduction to Carbon Monitor's methodology(***Scientific Data***) :

https://www.nature.com/articles/s41597-020-00708-7.pdf

Coupling Carbon Monitor with satellite observations(***GRL***) :

https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2020GL090244

Carbon Monitor combined with NASA's OCO2 satellite to reflect global carbon emissions changes(***Science Advances***) :

https://www.science.org/doi/10.1126/sciadv.abf9415

Carbon Monitor combined with satellite data to reflect the rapid recovery of carbon emissions in China(***Science Advances)*** :

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7821878/pdf/abd4998.pdf

Global carbon emission trends based on Carbon Monitor data (***Nature Climate Change***) :

https://essd.copernicus.org/articles/12/3269/2020/

https://www.nature.com/articles/s41558-021-01001-0

The world's first near-real-time carbon map based on Carbon Monitor(***The Innovation***):

https://www.cell.com/the-innovation/pdf/S2666-6758(21)00107-7.pdf

Take away

Different GHGs emissions require different quantification approaches

- **CO_2**: Carbon satellite technology not yet mature → optimized **bottom-up inventories** enable near-real-time emission accounting
- **CH_4**: Presence of ultra-emitters' leaks → requires **top-down inversions** with multi-source satellite observations

Our dataset: near-real-time, high-resolution

- Captures short-term events (holidays, lockdowns, extreme events)
- Provides sectoral and regional insights

Applications across fields

- Science – atmospheric models, emission dynamics
- Policy – Paris targets, transparency, carbon markets
- Society & Engineering – energy systems, transport, urban studies

Open collaboration potential

- Broad applicability across academic, policy, and industry communities

GRACED

https://carbonmonitor-graced.com/

- **Time coverage: since 2019**

Near-real-time
Global Gridded Daily Carbon Emissions Dataset

Thanks!

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