Supplementary Information

Siberian and temperate ecosystems shape Northern Hemisphere atmospheric CO$_2$ seasonal amplification

Xin Lin$^{a,1}$, Brendan M. Rogers$^b$, Colm Sweeney$^c$, Frédéric Chevallier$^d$, Mikhail Arshinov$^e$, Edward Dlugokencky$^c$, Toshinobu Machida$^f$, Motoki Sasakawa$^f$, Pieter Tans$^c$, Gretchen Keppel-Aleks$^{a,1}$

$^a$Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI 48109, USA
$^b$Woods Hole Research Center, Falmouth, MA 02540, USA
$^c$Global Monitoring Laboratory, National Oceanic and Atmospheric Administration, Boulder, CO 80305, USA
$^d$Laboratoire des Sciences du Climat et de l’Environnement/Institut Pierre Simon Laplace, Commissariat à l’Énergie Atomique et aux Énergies Alternatives–CNRS–Université de Versailles Saint-Quentin-en-Yvelines, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
$^e$V. E. Zuev Institute of Atmospheric Optics, Russian Academy of Sciences, Siberian Branch, Tomsk 634055, Russia
$^f$Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Ibaraki, 305-8506, Japan

$^1$To whom correspondence may be addressed. Email: xinlinn@umich.edu or gkeppela@umich.edu

This PDF file includes:

- Tables S1 to S11
- Figures S1 to S24
- SI References

www.pnas.org/cgi/doi/10.1073/pnas.1914135117
**Table S1** The geographical areas (unit: $10^6$ km$^2$) for the 13 tagged regions and six aggregated regions, corresponding to Fig. 1.

| Aggregated region | Tagged region | Geographical areas |
|-------------------|---------------|--------------------|
| NH_HighNA (15.5)  | NA_Arc        | 12.2               |
|                   | NA_Bor        | 3.3                |
| NH_HighEU (4.0)   | EU_Arc        | 2.9                |
|                   | EU_Bor        | 1.1                |
| NH_HighSIB (14.2) | SIB_Arc       | 9.2                |
|                   | SIB_BorEn     | 2.9                |
|                   | SIB_BorDn     | 2.0                |
| NH_Mid (45.8)     | NH_MidNat     | 41.6               |
|                   | NH_MidCrop    | 4.2                |
| NH_Trop (58.0)    | NH_TropNat    | 55.5               |
|                   | NH_TropCrop   | 2.5                |
| SH (68.5)         | SH_Trop       | 50.9               |
|                   | SH_ExTrop     | 17.6               |
**Table S2** Configurations of CO$_2$ inversion systems for CAMSv17r1 and CT2017.

|                     | CAMSv17r1                      | CT2017                       |
|---------------------|-------------------------------|------------------------------|
| Available period    | 1979–2017                     | 2000–2016                    |
| Resolution          | 1.875° × 3.75°                | 1° × 1°                      |
|                     | 39 vertical layers            | 25 vertical layers           |
| Transport model     | LMDz5A                        | TM5                          |
| Meteorology         | ERA-Interim                   | ERA-Interim                  |
| Observation         | Surface observations from 111 sites, Siberian tall tower measurements not included | 254 sites, including aircraft and ship measurements, Siberian tall tower measurements also included |
| Prior fluxes        | Fossil fuel                   | ODIAC2016 / “Miller”         |
|                     | EDGAR v4.2 / CDIAC / GCP     | ODIAC2016 / “Miller”         |
|                     | Ocean                         | OIF / Ref. 2                 |
|                     | Ref. 1                        | OIF / Ref. 2                 |
|                     | Biomass burning               | GFED4.1s / GFAS              |
|                     | GFED4.1s / GFED_CM            | GFED4.1s / GFED_CM           |
|                     | Terrestrial biosphere         | ORCHIDEE v1.9.5.2            |
|                     | ORCHIDEE v1.9.5.2             | CASA                         |
| Assimilation technique | Variational                  | Ensemble                     |
| Data sources        | https://apps.ecmwf.int/datasets/data/cams-ghg-inversions/ | https://www.esrl.noaa.gov/gmd/ccgg/carbontracker/download.php |
| References          | Ref. 3–4                      | Ref. 5                       |
Table S3 Surface stations used in this study.

| Code  | Station                          | LAT (°) | LON (°) | ALT (m asl) | Contributor                  | Time period        | Latitude band | Assimilated in CAMSv17r1 |
|-------|----------------------------------|---------|---------|-------------|-----------------------------|------------------|---------------|-------------------------|
| 1     | ALT¹ Alert, Canada               | 82.45   | -62.52  | 210         | EC, NOAA/GML                | Flask: 1985–2017 | High-latitude | Yes                     |
| 2     | ASC¹ Ascension Island, UK        | -7.97   | -14.40  | 85          | Met Office (UK),            | Flask: 1979–2017 | SH            | Yes                     |
| 3     | AZR¹ Azores, Portugal            | 38.75   | -27.08  | 22          | INMIG, NOAA/GML             | Flask: 1979–2017 | Mid-latitude  | Yes                     |
| 4     | AZV² Azovo, Russia               | 54.71   | 73.03   | 160         | NIES/CGER, RAS             | Continuous: 2007–2017 | Mid-latitude  | No                      |
| 5     | BHD Baring Head Station, New Zealand | -41.41 | -174.87 | 85          | NIWA, NOAA/GML             | Flask: 1999–2017 | SH            | Yes                     |
| 6     | BRW¹ Utqiagvik (Barrow), USA     | 71.32   | -156.60 | 11          | NOAA/GML                  | Flask: 1971–2017 | High-latitude | Yes                     |
| 7     | BRZ² Berezorechka, Russia        | 56.15   | 84.33   | 248         | NIES/CGER, RAS             | Continuous: 2002–2017 | Mid-latitude  | No                      |
| 8     | CBA¹ Cold Bay, USA               | 55.20   | -162.72 | 25          | USNWS, NOAA/GML            | Flask: 1978–2017 | Mid-latitude  | Yes                     |
| 9     | CGO Cape Grim, Tasmania, Australia | -40.68 | -144.69 | 94          | CSIRO, NOAA/GML           | Flask: 1984–2017 | SH            | Yes                     |
| 10    | CRZ Crozet Island, France        | -46.43  | -51.85  | 197         | LSCE, NOAA/GML             | Flask: 1991–2017 | SH            | Yes                     |
| 11    | DEM¹ Demyanskoe, Russia          | 59.79   | 70.87   | 126         | NIES/CGER, RAS             | Continuous: 2005–2017 | Mid-latitude  | No                      |
| 12    | EIC Easter Island, Chile         | -27.16  | -109.43 | 47          | DMC, NOAA/GML              | Flask: 1994–2017 | SH            | Yes                     |
| 13    | GMI¹ Mariana Island, Guam        | 13.39   | 144.66  | 5           | Univ. of Guam, NOAA/GML    | Flask: 1978–2017 | Low-latitude  | Yes                     |
| 14    | HBA Halley Station, Antarctica, UK | -75.61 | -26.21  | 30          | BAC, NOAA/GML              | Flask: 1983–2017 | SH            | Yes                     |
| 15    | IGR² Igrim, Russia               | 63.19   | 64.41   | 56          | NIES/CGER, RAS             | Continuous: 2004–2013 | High-latitude | No                      |
| 16    | IZO¹ Izaña, Tenerife, Spain      | 28.31   | -16.50  | 2378        | AEMET, NOAA/GML            | Flask: 1991–2017 | Low-latitude  | Yes                     |
| 17    | KRS² Karasevoe, Russia           | 58.25   | 82.42   | 143         | NIES/CGER, RAS             | Continuous: 2004–2013 | Mid-latitude  | No                      |
| 18    | KUM¹ Cape Kumukahi, USA          | 19.52   | -154.82 | 3           | NOAA/GML                  | Flask: 1971–2017 | Low-latitude  | Yes                     |
| 19    | MBC¹ Mould Bay, Canada           | 76.25   | -119.35 | 32          | EC, NOAA/GML              | Flask: 1980–1997 | High-latitude | Yes                     |
| 20    | MBD¹ Mace Head, Ireland          | 53.33   | -9.90   | 8           | NOAA/GML                  | Flask: 1991–2017 | Mid-latitude  | Yes                     |
| 21    | MID¹ Midway, USA                 | 28.22   | -177.37 | 4           | USFWS, NOAA/GML            | Flask: 1985–2017 | Low-latitude  | Yes                     |
| 22    | MLO¹ Mauna Loa, USA              | 19.54   | -155.58 | 3399        | NOAA/GML                  | Flask: 1969–2017 | Low-latitude  | Yes                     |
| 23    | NMB¹ Gobabeb, Namibia            | -23.58  | -15.03  | 456         | GTRC, NOAA/GML            | Flask: 1997–2017 | SH            | Yes                     |
| 24    | NOY¹ Noyabrsk, Russia            | 63.43   | 75.78   | 151         | NIES/CGER, RAS             | Continuous: 2005–2017 | High-latitude | No                      |
| 25    | NWI¹ Niwot Ridge, USA            | 40.05   | -105.59 | 3523        | INSTAAR, NOAA/GML         | Flask: 1967–2017 | Mid-latitude  | Yes                     |
| 26    | PSA¹ Palmer Station, Antarctica, USA | -64.92 | -64.00  | 10          | NSF, NOAA/GML            | Flask: 1978–2017 | SH            | Yes                     |
| 27    | SEY¹ Mahe Island, Seychelles     | -4.68   | 55.53   | 2           | SBS, NOAA/GML             | Flask: 1980–2017 | SH            | Yes                     |
| 28    | SHM¹ Shemya Island, USA          | 52.75   | 174.10  | 26          | Chugach, NOAA/GML        | Flask: 1985–2017 | Mid-latitude  | Yes                     |
| No. | Code | Location                        | Latitude  | Longitude  | Institution                                      | Interval      | Region   | Data Availability |
|-----|------|---------------------------------|-----------|------------|--------------------------------------------------|--------------|----------|-------------------|
| 29  | SMO  | Tutuila, American Samoa         | -15.25    | -170.56    | 42 NOAA/GML                                      | Flask: 1972–2017 | SH       | Yes               |
| 30  | SPO  | South Pole, Antarctica, USA     | -89.98    | -24.80     | 2810 NSF, NOAA/GML                               | Flask: 1975–2017 | SH       | Yes               |
| 31  | STM  | Ocean Station M, Norway         | 66.00     | 2.00       | 7 NMI, NOAA/GML                                  | Flask: 1981–2009 | High-latitude | Yes               |
| 32  | SUM  | Summit, Denmark                 | 72.58     | -38.48     | 3215 NSF, NOAA/GML                               | Flask: 1997–2017 | High-latitude | Yes               |
| 33  | SYO  | Syowa Station, Antarctica, Japan| -69.01    | 39.59      | 14 NIPR, NOAA/GML                                | Flask: 1986–2017 | SH       | Yes               |
| 34  | SVV  | Savvushka, Russia               | 51.33     | 82.13      | 547 NIES/CGER, RAS                               | Continuous: 2006–2014 | Mid-latitude | No                |
| 35  | TER  | Teriberka, Russia               | 69.20     | 35.10      | 40 MGO                                           | Flask: 1988–2017 | High-latitude | No                |
| 36  | TIK  | Tiksi, Russia                   | 71.60     | 128.89     | 29 MGO, NOAA/GML                                 | Flask: 2011–2017 | High-latitude | No                |
| 37  | USH  | Ushuaia, Argentina              | -54.85    | -68.31     | 12 SMN, NOAA/GML                                 | Flask: 1994–2017 | SH       | Yes               |
| 38  | VGN  | Vaganovo, Russia                | 54.50     | 62.32      | 277 NIES/CGER, RAS                               | Continuous: 2008–2017 | Mid-latitude | No                |
| 39  | YAK  | Yakutsk, Russia                 | 62.09     | 129.36     | 341 NIES/CGER, RAS                               | Continuous: 2005–2013 | High-latitude | No                |
| 40  | ZEP  | Zeppelin station, Norway and Sweden | 78.91     | 11.89      | 479 MISU, NOAA/GML                               | Flask: 1994–2017 | High-latitude | Yes               |

1 See Ref. 6, retrieved from [ftp://aftp.cmdl.noaa.gov/data/trace_gases/co2/flask/surface/](ftp://aftp.cmdl.noaa.gov/data/trace_gases/co2/flask/surface/)
2 See Ref. 7–8, retrieved from [http://db.cger.nies.go.jp/portal/geds/atmosphericAndOceanicMonitoring/](http://db.cger.nies.go.jp/portal/geds/atmosphericAndOceanicMonitoring/)
3 Retrieved from [https://gaw.kishou.go.jp/](https://gaw.kishou.go.jp/)

Abbreviations:
AEMET – Agencia Estatal de Meteorología, Spain; BAC – British Antarctic Survey; CSIRO – Commonwealth Scientific and Industrial Research Organisation, Australia; DMC – Dirección Meteorológica de Chile; EC – Environment Canada, Canada; GTRC – Gobabeb Training and Research Center; INAMET – Instituto Nacional de Meteorología e Geofísica, Portugal; INSTAAR – Institute of Arctic and Alpine Research, University of Colorado, USA; LSCE – Le Laboratoire des Sciences du Climat et l’Environnement; MISU – Meteorological Institute, University of Stockholm, Sweden; MGO – Voeikov Main Geophysical Observatory, Russia; NIES/CGER – National Institute for Environmental Studies/Center for Global Environmental Research, Japan; NMI – Norway Meteorological Institute, Norway; NSF – National Science Foundation, USA; NOAA/GML – National Oceanic and Atmospheric Administration/Global Monitoring Laboratory; RAS – Russian Academy of Science; SBS – Seychelles Bureau of Standards; SMN – Servicio Meteorológico Nacional, Argentina; USFWS – U. S. Fish and Wildlife Service; USNWS – U. S. National Weather Service
Table S4 Aircraft sampling networks and campaigns used in this study.

| Network/Campaign | Sampling domain                          | Flask/in-situ | Sampling frequency | Sampling altitude | Time period   | Scale         | Contributor | References |
|------------------|------------------------------------------|---------------|--------------------|-------------------|---------------|---------------|-------------|------------|
| 1                | NOAA’s GGGRN¹                           | Flask         | Vary               | 0–14870 m asl     | 1992–2016     | WMO X2007    | NOAA/GML    | Ref. 9     |
| 2                | CONTRAIL²                               | In-situ       | 10s                | 0–13107 m asl     | 2005–2015     | NIES09       | NIES, MRI   | Ref. 10–11 |
| 3                | NIES/CGER³                              | In-situ       | 2s                 | 100–3113 m agl    | 2001–2012     | NIES09       | NIES/CGER, RAS | Ref. 7     |

¹ Retrieved from: [https://www.esrl.noaa.gov/gmd/ccgg/obspack/data.php](https://www.esrl.noaa.gov/gmd/ccgg/obspack/data.php)
² Retrieved from: [http://www.cger.nies.go.jp/contrail/](http://www.cger.nies.go.jp/contrail/)
³ Retrieved from: [http://db.cger.nies.go.jp/portal/geds/atmosphericAndOceanicMonitoring](http://db.cger.nies.go.jp/portal/geds/atmosphericAndOceanicMonitoring)

Abbreviations:
CONTRAIL – Comprehensive Observation Network for TRace gases by AirLiner; MRI – Meteorological Research Institute, Japan; NIES/CGER – National Institute for Environmental Studies/Center for Global Environmental Research, Japan; NOAA/GML – National Oceanic and Atmospheric Administration/Global Monitoring Laboratory; NOAA’s GGGRN – National Oceanic and Atmospheric Administration’s Global Greenhouse Gas Reference Network; RAS – Russian Academy of Science
Table S5 Mean bias and RMSE of simulated CO$_2$ seasonal cycle amplitudes (SCA) and trends compared to ground observations in the NH for different station groups.

|                                | Mean SCA (ppm) | SCA trend (ppm·10yr$^{-1}$) |
|--------------------------------|----------------|-------------------------------|
|                                | Mean bias      | RMSE                         | Mean bias | RMSE |
| Assimilated sites (NOAA’s GGGRN sites) | 0.1±1.4        | 1.3                           | 0.15±0.31 | 0.34 |
| Non-assimilated sites (Russian sites)     | 1.5±3.5        | 3.7                           | 0.43      | 0.43 |
| High-latitude assimilated sites (60°–90°N) | 0.8±1.7        | 1.7                           | 0.12±0.23 | 0.25 |
| Mid-latitude assimilated sites (30°–60°N)    | -0.1±1.4       | 1.3                           | 0.42±0.27 | 0.48 |
| Low-latitude assimilated sites (0°–30°N)     | -0.6±0.5       | 0.7                           | -0.07±0.27| 0.25 |
Table S6 Regional contribution to CO₂ seasonal cycle amplitudes (SCA) for stations in the northern high-, mid-, and low-latitudes, based on simulated CO₂ and tracer concentrations from CAMSv17r1 during 1980–2017. For each latitude band, the regional contribution to SCA (in ppm) was averaged across stations, corresponding to Fig. 3A. The contribution in percentage (%) averaged across all stations in each latitude band is given as well in parentheses. Note that the contribution in percentage does not add up to 100%.

| 1980–2017 | Mean SCA | HighNA | HighEU | HighSIB | NH_Mid | NH_Trop | SH |
|-----------|----------|--------|--------|---------|--------|---------|----|
| High-latitude sites (60°–90°N; n=7) | 16.4±2.5 | 3.7±0.9 (22.5±4.1%) | 1.5±1.1 (8.5±5.5%) | 3.9±1.2 (23.5±5.3%) | 7.5±0.8 (46.1±6.1%) | -1.0±0.1 (-6.4±0.7%) | 0.4±0.0 (2.5±0.7%) |
| Mid-latitude sites (30°–60°N; n=5) | 13.0±4.1 | 2.5±1.1 (18.9±5.9%) | 0.6±0.2 (4.3±0.5%) | 3.4±2.3 (24.4±11.3%) | 6.1±1.7 (48.7±7.7%) | -0.6±0.6 (-3.5±5.5%) | 0.4±0.0 (3.4±1.0%) |
| Low-latitude sites (0°–30°N; n=5) | 7.1±1.2 | 0.9±0.3 (12.9±1.7%) | 0.3±0.1 (4.0±0.8%) | 1.4±0.6 (18.7±5.5%) | 3.4±0.8 (47.1±3.7%) | 0.8±0.7 (12.7±12.1%) | 0.2±0.2 (2.2±2.5%) |
Table S7 Regional contribution to CO$_2$ seasonal cycle amplitudes (SCA) for stations in the northern high-, mid-, and low-latitudes, based on simulated CO$_2$ and tracer concentrations from (a) CAMSv17r1 and (b) CT2017 during 2000–2016. For each latitude band, the regional contribution to SCA (in ppm) is averaged across stations. The contribution in percentage (%) averaged across all stations in each latitude band is given as well in parentheses. Note that the contribution in percentage does not add up to 100%.

(a)

| 2000–2016 | Mean SCA | HighNA | HighEU | HighSIB | NH_Mid | NH_Trop | SH |
|---|---|---|---|---|---|---|---|
| High-latitude sites (60°–90°N; n=7) | 17.5±2.6 | 3.8±1.0 (22.0±4.1%) | 1.4±1.1 (7.6±5.0%) | 4.4±1.2 (24.7±5.2%) | 7.9±0.9 (45.5±6.5%) | -0.9±0.1 (-5.5±0.6%) | 0.4±0.0 (2.4±0.7%) |
| Mid-latitude sites (30°–60°N; n=5) | 13.6±4.4 | 2.6±1.2 (18.3±5.3%) | 0.6±0.2 (4.1±0.4%) | 3.7±2.3 (25.3±10.4%) | 6.4±1.8 (48.2±7.6%) | -0.6±0.5 (-3.4±4.3%) | 0.4±0.0 (3.5±1.1%) |
| Low-latitude sites (0°–30°N; n=5) | 7.2±1.4 | 0.9±0.3 (12.7±1.7%) | 0.3±0.1 (3.9±0.8%) | 1.4±0.6 (18.7±5.0%) | 3.6±0.9 (48.9±3.5%) | 0.7±0.7 (11.0±11.2%) | 0.2±0.2 (2.4±2.6%) |

(b)

| 2000–2016 | Mean SCA | HighNA | HighEU | HighSIB | NH_Mid | NH_Trop | SH |
|---|---|---|---|---|---|---|---|
| High-latitude sites (60°–90°N; n=7) | 17.5±2.2 | 2.8±0.5 (15.9±2.1%) | 1.3±1.0 (7.1±4.6%) | 5.1±1.1 (29.3±5.3%) | 8.0±0.8 (46.1±4.5%) | -0.3±0.0 (-1.7±0.2%) | 0.1±0.0 (0.8±0.4%) |
| Mid-latitude sites (30°–60°N; n=5) | 14.1±4.4 | 1.9±0.8 (13.4±4.0%) | 0.6±0.2 (3.9±0.4%) | 4.4±2.4 (29.6±8.6%) | 6.8±1.5 (50.1±7.2%) | -0.2±0.1 (-1.2±1.1%) | 0.2±0.1 (1.8±1.3%) |
| Low-latitude sites (0°–30°N; n=5) | 7.5±1.8 | 0.8±0.2 (10.1±0.6%) | 0.3±0.1 (3.6±0.4%) | 1.7±0.7 (22.2±3.4%) | 4.2±1.1 (56.5±1.0%) | 0.2±0.2 (3.1±3.9%) | 0.2±0.1 (2.9±0.6%) |
Table S8 Contribution of different regions to changes in CO₂ seasonal cycle amplitudes (ΔSCA) for stations in northern high-, mid-, and low-latitudes, based on simulated CO₂ and tracer concentrations from CAMSv17r1 during 1980–2017. For each latitude band, the regional contribution to ΔSCA (in ppm) is averaged across stations, corresponding to **Fig. 3C**. The contribution in percentage (%) averaged across all stations in each latitude band is given as well in parentheses. Note that the contribution in percentage does not add up to 100%.

| 1980–2017 | ΔSCA | HighNA | HighEU | HighSIB | NH_Mid | NH_Trop | SH |
|-----------|------|--------|--------|---------|--------|---------|----|
| High-latitude sites (60°–90°N; n=7) | 3.8±0.4 | 0.5±0.4 (11.4±8.9%) | -0.1±0.1 (-2.2±2.3%) | 1.6±0.3 (42.2±3.7%) | 1.5±0.3 (38.8±9.8%) | 0.3±0.1 (7.0±2.1%) | 0.0±0.0 (0.9±1.0%) |
| Mid-latitude sites (30°–60°N; n=5) | 2.4±1.3 | 0.1±0.2 (7.9±12.9%) | 0.0±0.1 (1.7±4.2%) | 1.1±0.5 (61.4±36.5%) | 0.9±0.6 (31.8±21.9%) | 0.1±0.2 (-11.4±37.7%) | 0.1±0.0 (8.9±12.7%) |
| Low-latitude sites (0°–30°N; n=5) | 0.6±0.6 | 0.0±0.1 (1.5±32.1%) | 0.0±0.1 (1.2±%) | 0.1±0.2 (33.4±37.7%) | 0.6±0.2 (70.6±238.2%) | -0.2±0.2 (-15.3±240.1%) | 0.1±0.0 (13.6±26.9%) |
Table S9 Zonal analyses of the dominant contributor to changes in CO₂ seasonal cycle amplitudes (ΔSCA) for northern high-, mid-, and low-latitudes at (a) the surface, (b) 700 mb and (c) 500 mb. For each latitude band, the total area of pixels (S_pixel, in unit 10⁶ km²) with significant trends in SCA (p < 0.05) is given, as well as the area of pixels (and the area percentage) where a specific tagged region is identified as the dominant contributor.

(a) Surface

| 1980–2017 | S_pixel | HighNA | HighEU | HighSIB | NH_Mid | Others |
|------------|---------|--------|--------|---------|--------|--------|
| High-latitude pixels (60°–90°N) | 36.02 | 1.84 (5.1%) | 0 (0%) | 23.03 (63.9%) | 11.12 (30.9%) | 0.03 (0.1%) |
| Mid-latitude pixels (30°–60°N) | 68.82 | 0.46 (0.7%) | 0 (0%) | 19.46 (28.3%) | 47.62 (69.2%) | 1.28 (1.9%) |
| Low-latitude pixels (0°–30°N) | 63.90 | 0 (0%) | 0 (0%) | 4.17 (6.5%) | 26.84 (42.0%) | 32.90 (51.5%) |

(b) 700 mb

| 1980–2017 | S_pixel | HighNA | HighEU | HighSIB | NH_Mid | Others |
|------------|---------|--------|--------|---------|--------|--------|
| High-latitude pixels (60°–90°N) | 36.43 | 0.42 (1.2%) | 0 (0%) | 7.58 (20.8%) | 28.18 (77.3%) | 0.25 (0.7%) |
| Mid-latitude pixels (30°–60°N) | 79.73 | 0.08 (0.1%) | 0 (0%) | 8.05 (10.1%) | 71.19 (89.3%) | 0.41 (0.5%) |
| Low-latitude pixels (0°–30°N) | 45.41 | 0 (0%) | 0 (0%) | 5.61 (12.4%) | 8.34 (18.4%) | 31.47 (69.3%) |

(c) 500 mb

| 1980–2017 | S_pixel | HighNA | HighEU | HighSIB | NH_Mid | Others |
|------------|---------|--------|--------|---------|--------|--------|
| High-latitude pixels (60°–90°N) | 36.47 | 0 (0%) | 0 (0%) | 0 (0%) | 36.47 (100%) | 0 (0%) |
| Mid-latitude pixels (30°–60°N) | 77.05 | 0 (0%) | 0 (0%) | 0.45 (0.6%) | 75.71 (98.3%) | 0.88 (1.1%) |
| Low-latitude pixels (0°–30°N) | 21.86 | 0 (0%) | 0 (0%) | 0.12 (0.5%) | 6.87 (31.5%) | 14.86 (68.0%) |
Table S10 Zonal analyses of the regional contributions to changes in CO₂ seasonal cycle amplitudes (ΔSCA) for northern high-, mid-, and low-latitudes at (a) the surface, (b) 700 mb and (c) 500 mb. For each latitude band, the regional contribution to ΔSCA (in ppm) is averaged across pixels with positive and significant trends (i.e., ΔSCA > 0; \( p < 0.05 \)). The contribution in percentage (%) averaged across all pixels in each latitude band is given as well in parentheses. Note that the contribution in percentage does not add up to 100%.

(a) Surface

|                | 1980–2017 | ΔSCA   | HighNA     | HighEU      | HighSIB     | NH_Mid      | Others       |
|----------------|-----------|--------|------------|-------------|-------------|-------------|--------------|
| High-latitude pixels (60°–90°N) | 4.1±0.9  | 0.5±0.6 (10.6±13.5%) | -0.1±0.2 (-3.3±5.5%) | 2.1±1.0 (50.8±14.0%) | 1.1±0.5 (29.6±15.9%) | 0.5±0.2 (12.3±4.8%) |
| Mid-latitude pixels (30°–60°N)   | 3.4±2.2  | 0.2±0.6 (1.7±18.5%)  | 0.1±0.2 (1.4±4.9%)  | 1.2±0.7 (36.3±18.5%) | 1.6±1.5 (47.8±32.5%) | 0.5±0.5 (12.7±17.7%) |
| Low-latitude pixels (0°–30°N)    | 1.3±0.7  | 0.0±0.1 (-0.6±7.9%)  | 0.0±0.0 (0.3±2.6%)  | 0.4±0.2 (30.8±13.3%) | 0.8±0.5 (68.8±45.0%) | 0.2±0.7 (0.7±49.2%) |

(b) 700 mb

|                | 1980–2017 | ΔSCA   | HighNA     | HighEU      | HighSIB     | NH_Mid      | Others       |
|----------------|-----------|--------|------------|-------------|-------------|-------------|--------------|
| High-latitude pixels (60°–90°N) | 3.5±0.4  | 0.2±0.2 (6.7±5.8%)  | 0.0±0.0 (-0.4±1.3%) | 1.3±0.3 (37.8±7.3%) | 1.6±0.3 (45.4±8.5%) | 0.4±0.2 (10.5±5.9%) |
| Mid-latitude pixels (30°–60°N)   | 2.3±1.2  | 0.1±0.2 (3.9±8.1%)  | 0.0±0.1 (1.1±2.8%)  | 0.7±0.4 (30.2±11.3%) | 1.3±0.7 (66.7±31.1%) | 0.1±0.4 (-1.9±27.1%) |
| Low-latitude pixels (0°–30°N)    | 1.2±0.3  | 0.1±0.1 (6.8±9.0%)  | 0.0±0.0 (1.9±4.5%)  | 0.5±0.2 (46.3±16.4%) | 0.6±0.5 (60.9±52.2%) | -0.1±0.7 (-15.9±67.2%) |

(c) 500 mb

|                | 1980–2017 | ΔSCA   | HighNA     | HighEU      | HighSIB     | NH_Mid      | Others       |
|----------------|-----------|--------|------------|-------------|-------------|-------------|--------------|
| High-latitude pixels (60°–90°N) | 2.9±0.4  | 0.1±0.1 (4.0±3.1%)  | 0.0±0.0 (0.6±0.9%)  | 1.0±0.2 (33.9±4.5%) | 1.5±0.2 (51.6±5.3%) | 0.3±0.1 (9.9±4.6%) |
| Mid-latitude pixels (30°–60°N)   | 1.6±0.8  | 0.1±0.1 (1.3±7.4%)  | 0.0±0.0 (0.4±1.4%)  | 0.5±0.2 (32.0±10.9%) | 1.2±0.4 (88.6±34.4%) | -0.2±0.3 (-22.2±36.4%) |
| Low-latitude pixels (0°–30°N)    | 0.7±0.1  | 0.0±0.0 (5.4±4.2%)  | 0.0±0.0 (1.2±1.2%)  | 0.4±0.1 (53.2±10.1%) | 0.6±0.1 (96.1±21.2%) | -0.3±0.1 (-55.9±28.4%) |
Table S11 The annual mean fluxes and flux trends over the period 1980–2017 for the six major tagged regions (** \( p < 0.01, \) * \( p < 0.05 \)). For each tagged region, both integrated and per area annual mean fluxes or flux trends are given. Analyses are based on land fluxes from CAMSv17r1.

| Tagged Region | Annual mean fluxes | Flux trends |
|---------------|--------------------|-------------|
|               | Integrated (PgC·yr\(^{-1}\)) | Per area (gC·m\(^{-2}\)·yr\(^{-1}\)) | Integrated \((10^3\) PgC·yr\(^{-2}\)) | Per area (gC·m\(^{-2}\)·yr\(^{-2}\)) |
| NH HighNA     | -0.32 ± 0.13       | -20.82 ± 8.26 | -3.11 ± 1.85     | -0.20 ± 0.12       |
| NH HighEU     | -0.09 ± 0.05       | -21.96 ± 12.99 | -1.70 ± 0.73*    | -0.42 ± 0.18*      |
| NH HighSIB    | -0.17 ± 0.28       | -12.34 ± 20.09 | -18.82 ± 2.89**  | -1.33 ± 0.20**     |
| NH Mid        | -1.84 ± 0.37       | -40.11 ± 8.10  | -11.85 ± 5.21*   | 0.26 ± 0.11*       |
| NH Trop       | 0.46 ± 0.60        | 8.00 ± 10.42   | 8.24 ± 8.95      | 0.14 ± 0.15        |
| SH            | 0.03 ± 0.76        | 0.50 ± 11.03   | -36.45 ± 9.57*   | -0.53 ± 0.14*      |
**Figure S1** Flow chart showing definition of the 13 tagged regions for terrestrial ecosystems. The delineation of these regions was based on climate, continent and plant functional types (PFTs) from the Community Land Model version 5 (CLM5) for 2000. Of the 16 PFTs defined in CLM5 (see details in [http://www.cesm.ucar.edu/models/clm/surface.heterogeneity.html](http://www.cesm.ucar.edu/models/clm/surface.heterogeneity.html)), arctic PFTs include Arctic C3 grass and Broadleaf deciduous boreal shrubs, whereas boreal PFTs include Needleleaf evergreen boreal trees, Needleleaf deciduous boreal trees and Broadleaf deciduous boreal trees.
**Figure S2** Locations of assimilated surface stations in the Northern Hemisphere in the CO$_2$ inversions: (a) CAMSv17r1 and (b) CT2017. The green triangles in (a) represent the four marine boundary layer stations downwind of Siberia with data record dating back to the 1980s or earlier, i.e., Alert (ALT), Utqiagvik (Barrow, BRW), Cold Bay (CBA) and Shemya Island (SHM). The green circles in (b) indicate the inland tall towers in Siberia, which are assimilated in CT2017 but not in CAMSv17r1.
Figure S3 (a) Map of 13 surface stations in the Southern Hemisphere from the NOAA’s GGGRN used for evaluation. Only stations with records longer than 15 years were selected. (b) Comparison of simulated versus observed CO$_2$ SCA at these stations. The dotted and solid lines represent the unit line and least squares regression line, respectively. Error bars denote ±1σ standard deviation.
Figure S4 Spatial distribution of aircraft CO$_2$ vertical profiles from different networks: (a) NOAA’s GGGRN, (b) NIES/CGER, and (c) CONTRAIL. Observations from the three networks were combined and grouped based on GEOS-Chem $2^\circ \times 2.5^\circ$ model grids and 1 km altitude bins between 0 and 8 km (d). Grid cells are colored by observation density, $N_{(\text{year, month, altband})}$, which is defined as the number of different combinations of the year, month and altitude bin that an observation is sampled. We identify 17 grid cells with satisfactory record length ($\geq$ 10 yrs) and vertical profiles for model evaluation (noted as blue triangles; also see Fig. 1A and SI Appendix Fig. S5).
Figure S5 Time series of CO₂ concentrations between 0 km and 8 km from aircraft profiles at 17 selected grid cells for model evaluation. Each line represents an individual observation from a particular aircraft campaign within the pixel, colored by levels of CO₂ concentrations. Panels are arranged by latitudes and correspond to aircraft sites noted in Fig. 1A and SI Appendix Fig. S4d.
Figure S6 Simulated annual cycles of CO$_2$ (in black) and tracers (in colors) from different tagged regions at Utqiagvik (Barrow), Alaska, after removing long-term growth rates. The grey line indicates the observed CO$_2$ annual cycles after detrending. Note that for a specific year, the Julian days when the CO$_2$ and tracer curves reach the seasonal maxima or minima are not necessarily the same (phase shift).
Figure S7 Time series of observed and simulated CO₂ SCA at selected stations in the Northern Hemisphere from NOAA’s GGGRN and at the Russian station Teriberka (TER). For each panel, black dots indicate CO₂ SCA from observations, while red and blue dots indicate simulated SCA from CO₂ inversion products CAMSv17r1 and CT2017, respectively. Both observed and simulated CO₂ SCA from CAMSv17r1 were fitted over the time period when observations are available, with trends given as well (** $p < 0.01$, * $p < 0.05$). Solid and dotted lines indicate significant and non-significant trends, respectively. Panels are arranged by latitudes.
**Figure S8** Time series of observed and simulated CO₂ SCA at 13 selected stations in the Southern Hemisphere from NOAA’s GGGRN. For each panel, black dots indicate CO₂ SCA from observations, while red and blue dots indicate simulated SCA from CO₂ inversion products CAMSv17r1 and CT2017, respectively. Both observed and simulated CO₂ SCA from CAMSv17r1 were fitted over the time period when observations are available, with trends given as well (** $p < 0.01$, * $p < 0.05$). Solid and dotted lines indicate significant and non-significant trends, respectively. Panels are arranged by latitudes.
Figure S9 Evaluation of simulated versus observed CO$_2$ SCA at Russian sites. The simulated SCA are derived from model results with CAMSv17r1 (red) or CT2017 (blue). Observations from these Russian sites were assimilated in CT2017 but not in CAMSv17r1. The black dotted line represents the unit line, whereas the colored lines indicate the least squares regression lines between simulated versus observed CO$_2$ SCA. Error bars denote ±1σ.
Figure S10 Comparison of CO₂ SCA simulated by GEOS-Chem versus (a) LMDz and (b) TM5. The SCA simulated by LMDz or TM5 at various stations were extracted from the posterior concentration fields of the CO₂ inversion CAMSv17r1 or CT2017. For each group of the boxplot, the box on the left (with the y axis on the left side) shows statistics of the model-observation bias, whereas the box on the right (with the y axis on the right side) shows the relative bias with respect to the SCA simulated by LMDz or TM5. The orange, green and blue circles, bars and texts indicate data and results for high-latitude (60–90°N), mid-latitude (30–60°N), and low-latitude (0–30°N) stations, respectively. Only the 16 stations from NOAA’s GGGRN and the non-assimilated station Teriberka in Russia were included. Dotted and solid lines represent the unit line and least squares regression line, respectively. Error bars denote ±1σ.
**Figure S11** Simulated versus observed vertical profiles of CO$_2$ SCA at 17 aircraft sites. For each panel, black dots indicate CO$_2$ SCA from observations, while red and blue dots indicate simulated SCA from CO$_2$ inversion products CAMSv17r1 and CT2017, respectively. Both observed and simulated mean SCA were estimated over the time period when observations are available. Panels are arranged by latitudes and correspond to aircraft sites noted in Fig. 14. Error bars denote ±1σ.
Figure S12 Simulated versus observed vertical profiles of the Julian day for CO$_2$ seasonal cycle minimum ($D_{\text{min}}$) at 17 aircraft sites. For each panel, black dots indicate $D_{\text{min}}$ from observations, while red and blue dots indicate simulated $D_{\text{min}}$ from CO$_2$ inversion products CAMSv17r1 and CT2017, respectively. Both observed and simulated $D_{\text{min}}$ were estimated over the time period when observations are available. Panels are arranged by latitudes and correspond to aircraft sites noted in Fig. 1A. Error bars denote $\pm 1\sigma$. 
Figure S13 Simulated versus observed vertical profiles of the Julian day for CO$_2$ seasonal cycle maximum ($D_{\text{max}}$) at 17 aircraft sites. For each panel, black dots indicate $D_{\text{max}}$ from observations, while red and blue dots indicate simulated $D_{\text{max}}$ from CO$_2$ inversion products CAMSv17r1 and CT2017, respectively. Both observed and simulated $D_{\text{max}}$ were estimated over the time period when observations are available. Panels are arranged by latitudes and correspond to aircraft sites noted in Fig. 1A. Error bars denote ±1σ.
Figure S14 Simulated versus observed vertical profiles of the downward zero-crossing day for CO$_2$ seasonal cycle ($D0_{down}$) at 17 aircraft sites. For each panel, black dots indicate $D0_{down}$ from observations, while red and blue dots indicate simulated $D0_{down}$ from CO$_2$ inversion products CAMSv17r1 and CT2017, respectively. Both observed and simulated $D0_{down}$ were estimated over the time period when observations are available. Panels are arranged by latitudes and correspond to aircraft sites noted in Fig. 1A. Error bars denote ±1σ.
**Figure S15** Simulated versus observed vertical profiles of the upward zero-crossing day for CO2 seasonal cycle ($D_0_{\text{up}}$) at 17 aircraft sites. For each panel, black dots indicate $D_0_{\text{up}}$ from observations, while red and blue dots indicate simulated $D_0_{\text{up}}$ from CO2 inversion products CAMSv17r1 and CT2017, respectively. Both observed and simulated $D_0_{\text{up}}$ were estimated over the time period when observations are available. Panels are arranged by latitudes and correspond to aircraft sites noted in Fig. 1A. Error bars denote ±1σ.
Figure S16 Contribution of the six major tagged regions to site-level (a) CO$_2$ SCA and (b) $\Delta$SCA normalized by region size (in ppm·10$^{-6}$·km$^{-2}$), based on simulations using the inverted fluxes from CAMSv17r1 for 1980–2017. The orange, green and blue bars represent flux imprints from different tagged regions on x-axis for northern high-latitude (60–90°N; n=7), mid-latitude (30–60°N; n=5) and low-latitude (0–30°N; n=5) stations, respectively. Only the 16 stations from NOAA’s GGGRN and the non-assimilated station Teriberka in Russia were included.
**Figure S17** Contribution of different regions to CO$_2$ seasonal cycle amplitudes (SCA, in ppm) for 17 stations in the Northern Hemisphere, based on simulated CO$_2$ and tracer concentrations from CAMSv17r1 during 1980–2017. For each panel, the numbers on the top right indicate the observed (black) and simulated (red) mean SCA over the time period when observations are available. Panels are arranged by latitudes.
Figure S18 Contribution of the six major tagged regions to site-level CO₂ SCA, based on simulations using the inverted fluxes from (a) CAMSv17r1 and (b) CT2017 for 2000–2016. The orange, green and blue bars represent flux imprints from different tagged regions on x-axis for northern high-latitude (60–90°N; n=7), mid-latitude (30–60°N; n=5) and low-latitude (0–30°N; n=5) stations, respectively, with the numbers in the parentheses showing the mean SCA averaged within station groups. Only the 16 stations from NOAA's GGGRN and the non-assimilated station Teriberka in Russia are included.
Figure S19 Contribution of different regions to changes in CO$_2$ seasonal cycle amplitudes ($\Delta$SCA, in ppm) for 17 stations in the Northern Hemisphere, based on simulated CO$_2$ and tracer concentrations from CAMSv17r1 during 1980–2017. For each panel, the numbers on the top right indicate the observed (black) and simulated (red) mean $\Delta$SCA over the time period when observations are available. Significance of trends is notated for CO$_2$ and respective tracers (** $p < 0.01$, * $p < 0.05$, + $p < 0.10$). Panels are arranged by latitudes.
Figure S20 Trend in NEE seasonality for 1980–2017, based on fluxes from CAMSv17r1. (a) presents the spatial pattern of trend in the NEE seasonal amplitude (SCA\textsubscript{NEE}). Only pixels with significant trends ($p < 0.05$) are shaded. The bold black lines delineate the three high-latitude tagged regions, i.e., NH\_HighNA, NH\_HighEU and NH\_HighSIB. (b) presents a comparison of seasonal carbon exchanges between 2013–2017 and 1980–1984 averaged over Siberian ecosystems (i.e. the tagged region NH\_HighSIB). The error bars for monthly fluxes are $\pm 1\sigma$ posterior error standard deviation using the Monte Carlo method described in Ref. 12. The seasonal carbon exchange based on fluxes from CT2017 during 2013–2016 is also presented for comparison.
Figure S21 Time series of simulated and observed CO$_2$ SCA at the altitude 3–4 km for the 17 pixels selected for vertical profile evaluation. For each panel, black dots indicate CO$_2$ SCA from observations, while red and blue dots indicate simulated SCA from CO$_2$ inversion products CAMSv17r1 and CT2017, respectively. Both observed and simulated SCA from CAMSv17r1 were fitted over the time period when observations are available, show in black and red lines respectively, with trends given as well (** $p < 0.01$, * $p < 0.05$). Solid and dotted lines indicate significant and non-significant trends, respectively. For simulated SCA from CAMSv17r1, the fitted line and trend over the whole simulation period 1980–2017 are also shown in purple. Panels are arranged by latitudes and correspond to the aircraft sites noted in Fig. 1A.
Figure S22 Evaluation of simulated versus observed vertical profiles of CO₂ SCA trends at 17 aircraft sites. For each panel, black dots indicate SCA trends from observations, while red and blue dots indicate simulated SCA trends from CO₂ inversion products CAMSv17r1 and CT2017, respectively. Both observed and simulated SCA trends are estimated over the time period when observations are available. Filled circles represent significant trends ($p < 0.05$), whereas open circles with “+” represent marginally significant trends ($p < 0.1$). Panels are arranged by latitudes and correspond to the aircraft sites noted in Fig. 1A. Error bars denote ±1σ.
Figure S23 Significance of the SCA trend as a function of data record length based on model results at 17 aircraft sites. For the definition of detectability of significant trend, see Materials and Methods for details. The point of intersection between each curve and the horizontal dotted line represents the minimal data length required to achieve ≥50% detectability of significant trend. Panels are arranged by latitudes and correspond to the aircraft sites noted in Fig. 14.
Figure S24 Footprint maps showing origins of air masses for Alert (ALT), Utqiagvik (Barrow, BRW), Cold Bay (CBA) and Shemya Island (SHM). For each station, individual 168-hour backward trajectories were reconstructed for the year 2015 at an hourly frequency, using the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (13–15) driven by the 3-hourly meteorological fields from the Global Data Assimilation System (GDAS) archive run by National Centers for Environmental Prediction (NECP). Maps are color-coded based on the number of trajectories passing through each grid cell. The bold black lines delineate the three high-latitude tagged regions, i.e., NH_HighNA, NH_HighEU and NH_HighSIB.
References

1. Landschützer P, et al. (2015) The reinvigoration of the Southern Ocean carbon sink. Science 349(6253):1221–4.

2. Takahashi T, et al. (2009) Climatological mean and decadal change in surface ocean pCO$_2$ and net sea–air CO$_2$ flux over the global oceans. Deep Sea Res Part II Top Stud Oceanogr 56(8–10):554–577.

3. Chevallier F, et al. (2010) CO$_2$ surface fluxes at grid point scale estimated from a global 21 year reanalysis of atmospheric measurements. J Geophys Res 115(D21):D21307.

4. Chevallier F, et al. (2005) Inferring CO$_2$ sources and sinks from satellite observations: Method and application to TOVS data. J Geophys Res 110(D24):D24309.

5. Peters W, et al. (2007) An atmospheric perspective on North American carbon dioxide exchange: CarbonTracker. Proc Natl Acad Sci U S A 104(48):18925–30.

6. Dlugokencky EL, et al. (2018) Atmospheric Carbon Dioxide Dry Air Mole Fractions from the NOAA ESRL Carbon Cycle Cooperative Global Air Sampling Network, 1968-2017, Version: 2018-07-31 Available at: ftp://aftp.cmdl.noaa.gov/data/trace_gases/co2/flask/surface/.

7. Sasakawa M, et al. (2013) Aircraft and tower measurements of CO$_2$ concentration in the planetary boundary layer and the lower free troposphere over southern taiga in West Siberia: Long-term records from 2002 to 2011. J Geophys Res Atmos 118(16):9489–9498.

8. Sasakawa M, et al. (2010) Continuous measurements of methane from a tower network over Siberia. Tellus B Chem Phys Meteorol 62(5):403–416.

9. Sweeney C, et al. (2018) NOAA Carbon Cycle and Greenhouse Gases Group aircraft-based measurements of CO$_2$, CH$_4$, CO, N$_2$O, H$_2$ and SF$_6$ in flask-air samples taken since 1992 (NOAA Earth System Research Laboratory, Global Monitoring Division) Available at: http://dx.doi.org/10.7289/V5N58JMF.

10. Machida T, Matsueda H, Sawa Y, Niwa Y (2018) Atmospheric CO$_2$ mole fraction data of CONTRAIL-CME. doi:10.17595/20180208.001.

11. Machida T, et al. (2008) Worldwide Measurements of Atmospheric CO$_2$ and Other Trace Gas Species Using Commercial Airlines. J Atmos Ocean Technol 25(10):1744–1754.

12. Chevallier F, Bréon F-M, Rayner PJ (2007) Contribution of the Orbiting Carbon Observatory to the estimation of CO$_2$ sources and sinks: Theoretical study in a variational data assimilation framework. J Geophys Res 112(D9):D09307.

13. Draxler RR, Hess GD (1998) An overview of the HYSPLIT_4 modeling system of trajectories, dispersion, and deposition. Aust Meteor Mag 47:295–308.

14. Draxler RR (1999) HYSPLIT4 user’s guide. NOAA Tech. Memo. ERL ARL-230 (Silver Spring, MD).

15. Stein AF, et al. (2015) NOAA’s HYSPLIT atmospheric transport and dispersion modeling system. Bull Am Meteorol Soc 96(12):2059–2077.