



*Supplement of*

## **Assessing the consistency of $XCO_2$ products from DQ-1 ACDL and passive satellites using a unified comparison framework**

**Yike Wang et al.**

*Correspondence to:* Ge Han (udhan@whu.edu.cn)

The copyright of individual parts of the supplement might differ from the article licence.

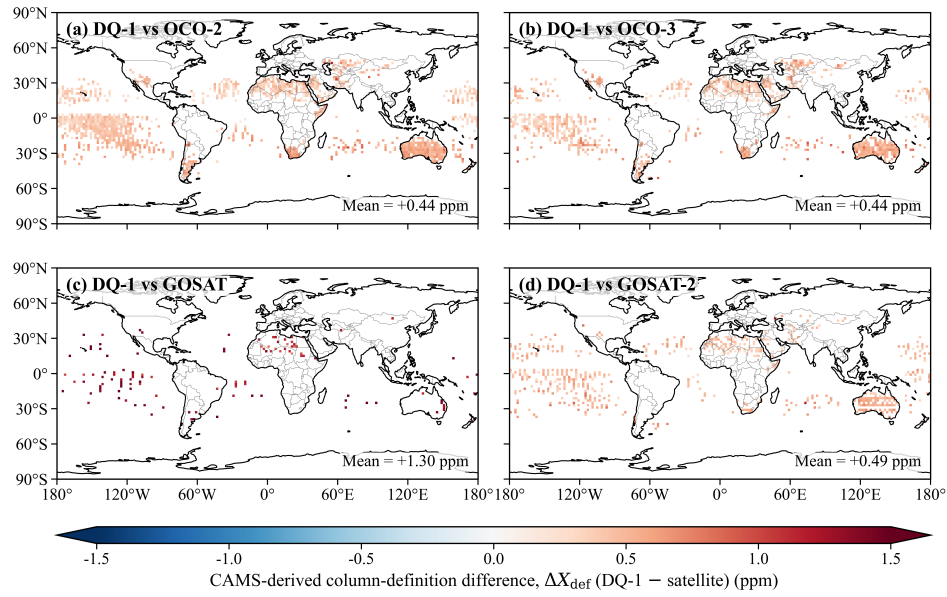


**Figure S1. Spatial distributions of the CAMS-derived  $XCO_2$  column-definition differences between DQ-1 and (a) OCO-2, (b) OCO-3, (c) GOSAT, and (d) GOSAT-2 for the collocated samples. The column-definition difference is defined as  $XCO_2$  (DQ-1 definition) –  $XCO_2$  (satellite definition), and the mean value for each satellite pair is shown in the lower-right corner of each panel.**

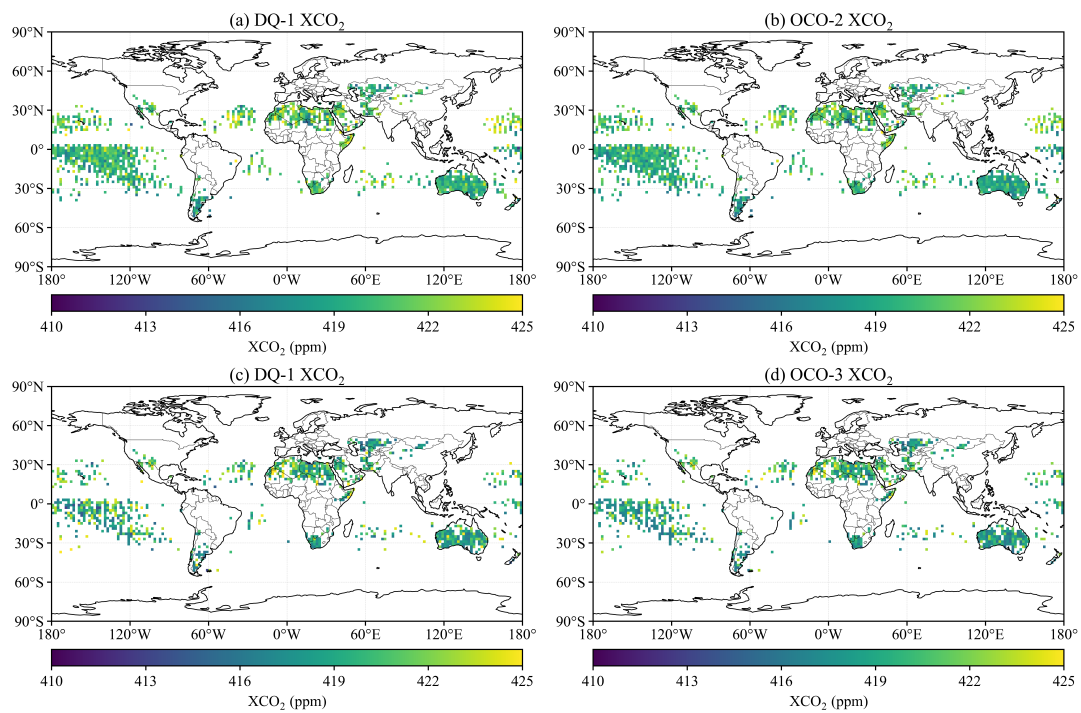


**Figure S2. Spatial distributions of paired DQ-1, OCO-2, and OCO-3 XCO<sub>2</sub> samples over the selected 2° comparison grid cells.**

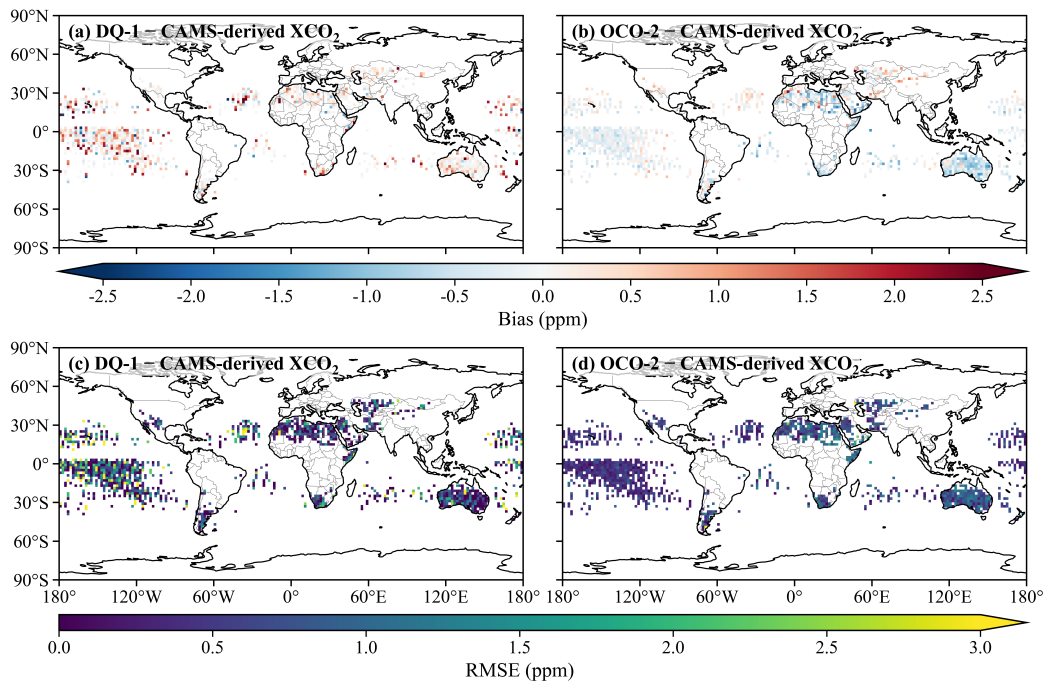


**Figure S3. Spatial distributions of daytime bias and RMSE relative to CAMS-derived XCO<sub>2</sub> for DQ-1 and OCO-2, based on the same DQ-1–OCO-2 collocated samples. Panels (a, b) show the biases for DQ-1 and OCO-2, respectively, and panels (c, d) show the corresponding RMSEs. Bias is defined as satellite XCO<sub>2</sub> – CAMS-derived XCO<sub>2</sub>.**

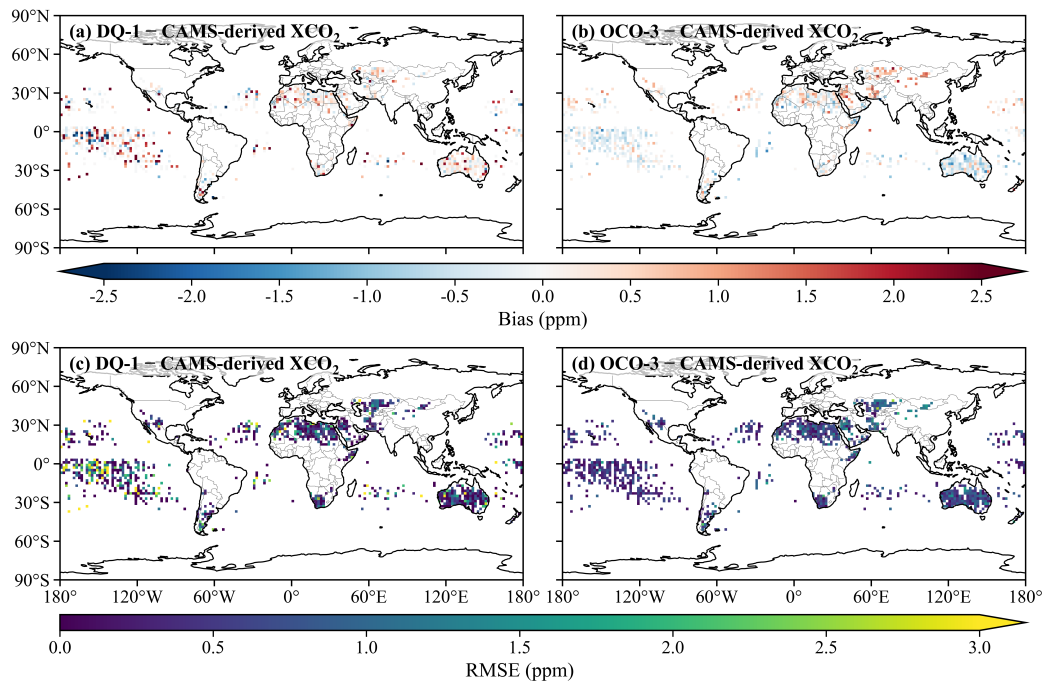


**Figure S4.** Spatial distributions of daytime bias and RMSE relative to CAMS-derived XCO<sub>2</sub> for DQ-1 and OCO-3, based on the same DQ-1–OCO-3 collocated samples. Panels (a, b) show the biases for DQ-1 and OCO-3, respectively, and panels (c, d) show the corresponding RMSEs. Bias is defined as satellite XCO<sub>2</sub> – CAMS-derived XCO<sub>2</sub>.

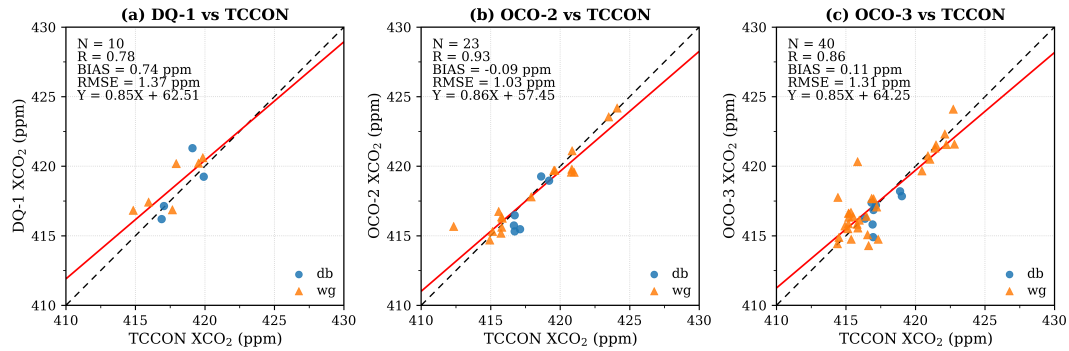


**Figure S5.** Scatterplot comparisons of DQ-1, OCO-2, and OCO-3 XCO<sub>2</sub> with TCCON observations at the Darwin (db) and Wollongong (wg) sites in Australia. Panels (a–c) show the comparisons for DQ-1, OCO-2, and OCO-3, respectively. The dashed black line denotes the 1:1 line, and the red line shows the linear regression fit.

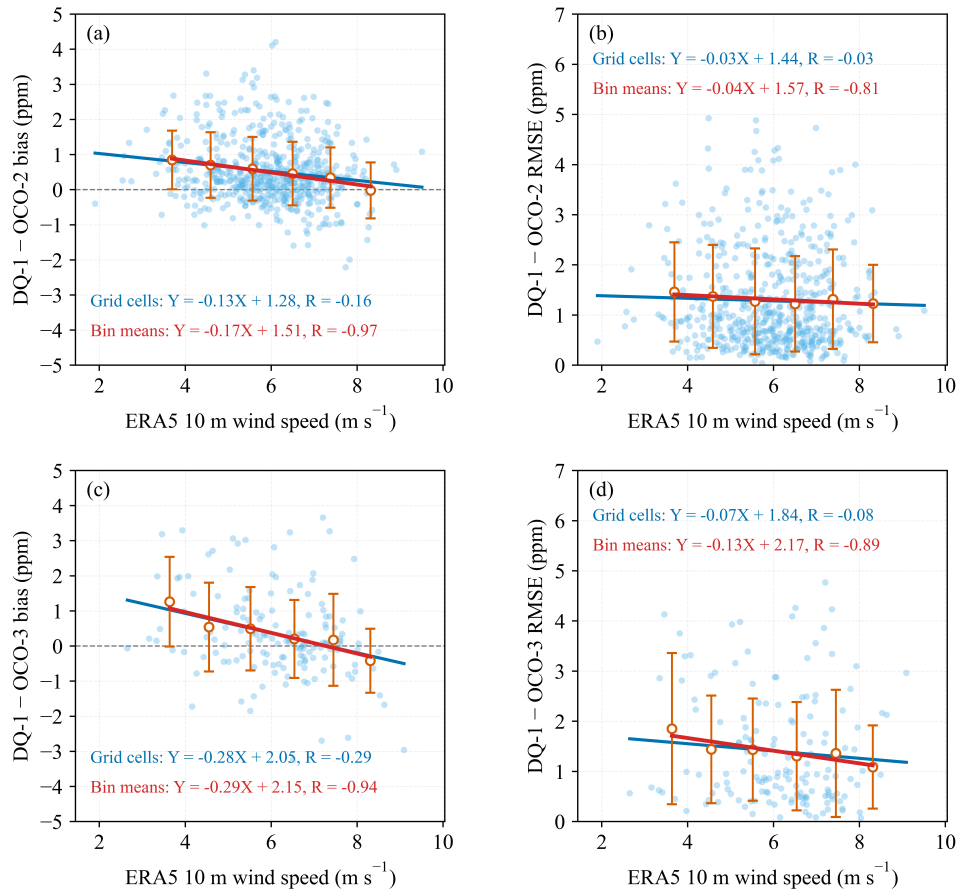


**Figure S6. Dependence of oceanic DQ-1-OCO-2 and DQ-1-OCO-3 bias and RMSE on ERA5 10 m wind speed. Panels (a, b) show DQ-1-OCO-2 and panels (c, d) show DQ-1-OCO-3. Light blue dots denote individual oceanic  $2^\circ$  grid cells, while orange circles and error bars show 1  $\text{m s}^{-1}$  wind-speed-bin means  $\pm 1$  standard deviation. Blue and red lines show linear least-squares fits to the individual grid-cell values and displayed bin means, respectively; the corresponding regression equations and Pearson correlation coefficients are annotated in each panel. Bias is defined as DQ-1 minus OCO.**

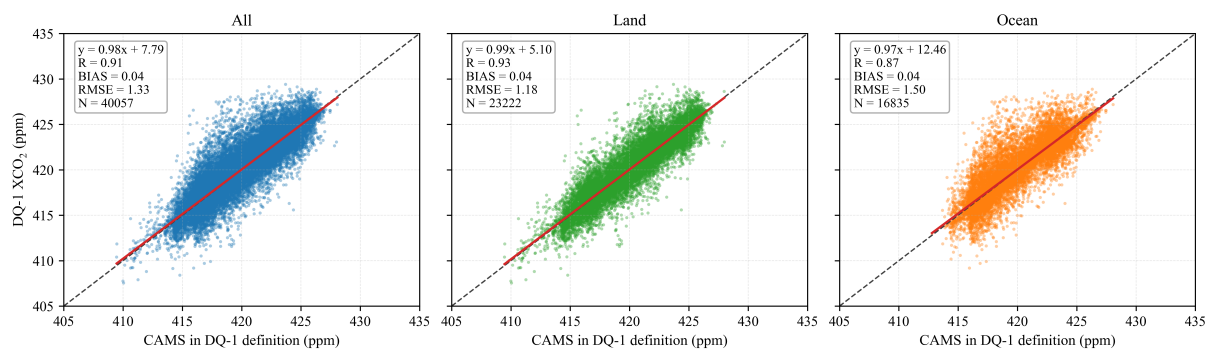


**Figure S7. Scatterplot comparison between nighttime DQ-1 XCO<sub>2</sub> and CAMS-derived XCO<sub>2</sub> for daily 2° paired samples under the DQ-1 column definition.**

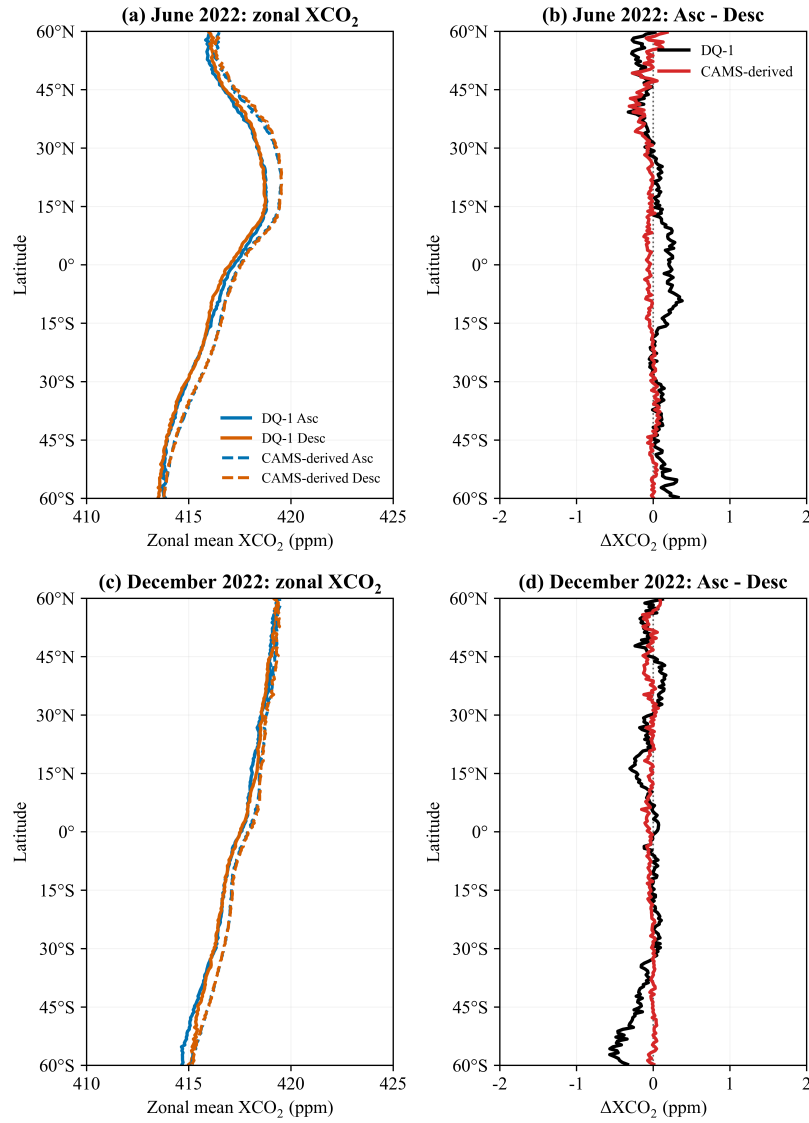


**Figure S8. Zonal-mean comparison of ascending (daytime) and descending (nighttime) DQ-1 XCO<sub>2</sub> and the corresponding CAMS-derived XCO<sub>2</sub> under the DQ-1 column definition for (a, b) June 2022 and (c, d) December 2022. Panels (a) and (c) show the zonal-mean XCO<sub>2</sub> distributions for the Asc and Desc observations, and panels (b) and (d) show the corresponding Asc-minus-Desc (daytime-minus-nighttime) differences for DQ-1 and CAMS-derived XCO<sub>2</sub>.**

**Table S1. Distribution of valid satellite–TCCON collocations across TCCON sites. Values are reported as N (%), with percentages relative to the total number of collocations for each satellite.**

| TCCON site | OCO-2<br>N (%) | OCO-3<br>N (%) | GOSAT<br>N (%) | GOSAT-2<br>N (%) | DQ-1<br>N (%) |
|------------|----------------|----------------|----------------|------------------|---------------|
| an         | –              | 1 (0.2)        | –              | –                | 1 (0.6)       |
| br         | 1 (0.3)        | –              | –              | 3 (0.3)          | 3 (1.8)       |
| bu         | 3 (0.9)        | 4 (0.8)        | 4 (0.9)        | 9 (1.0)          | 2 (1.2)       |
| ci         | 33 (9.9)       | 57 (11.5)      | 173 (38.6)     | 152 (17.3)       | 7 (4.2)       |
| db         | 6 (1.8)        | 8 (1.6)        | 5 (1.1)        | 4 (0.5)          | 4 (2.4)       |
| df         | 58 (17.4)      | 63 (12.7)      | 122 (27.2)     | 99 (11.2)        | 19 (11.4)     |
| et         | 16 (4.8)       | –              | –              | 27 (3.1)         | 7 (4.2)       |
| gm         | 5 (1.5)        | 22 (4.4)       | 4 (0.9)        | 10 (1.1)         | 6 (3.6)       |
| hf         | 4 (1.2)        | 2 (0.4)        | –              | 24 (2.7)         | 5 (3.0)       |
| hw         | 6 (1.8)        | 32 (6.5)       | –              | 20 (2.3)         | 3 (1.8)       |
| iz         | 4 (1.2)        | 14 (2.8)       | –              | 5 (0.6)          | 1 (0.6)       |
| js         | 9 (2.7)        | 17 (3.4)       | 20 (4.5)       | 30 (3.4)         | 3 (1.8)       |
| ka         | 15 (4.5)       | 12 (2.4)       | –              | 21 (2.4)         | 3 (1.8)       |
| lr         | 21 (6.3)       | 47 (9.5)       | 1 (0.2)        | 77 (8.8)         | 10 (6.0)      |
| ni         | 24 (7.2)       | 34 (6.9)       | –              | 52 (5.9)         | 8 (4.8)       |
| ny         | 4 (1.2)        | –              | –              | –                | 10 (6.0)      |
| oc         | 25 (7.5)       | 41 (8.3)       | 22 (4.9)       | 112 (12.7)       | 15 (9.0)      |
| or         | 4 (1.2)        | 14 (2.8)       | 5 (1.1)        | 13 (1.5)         | 1 (0.6)       |
| pa         | 24 (7.2)       | 39 (7.9)       | 16 (3.6)       | 39 (4.4)         | 16 (9.6)      |
| pr         | 8 (2.4)        | 16 (3.2)       | 2 (0.4)        | 16 (1.8)         | 5 (3.0)       |
| rj         | 9 (2.7)        | 7 (1.4)        | –              | 17 (1.9)         | 7 (4.2)       |
| so         | 10 (3.0)       | –              | 9 (2.0)        | 13 (1.5)         | 6 (3.6)       |
| wg         | 17 (5.1)       | 32 (6.5)       | 17 (3.8)       | 34 (3.9)         | 6 (3.6)       |
| xh         | 27 (8.1)       | 33 (6.7)       | 48 (10.7)      | 103 (11.7)       | 18 (10.8)     |
| Total      | 333            | 495            | 448            | 880              | 166           |

**Table S2. Satellite–TCCON validation statistics, site-level variability, and 95 % confidence intervals. The 95 % confidence intervals (CIs) of the pooled bias and RMSE are defined by the 2.5th and 97.5th percentiles of 20 000 TCCON-site cluster-bootstrap realizations. Interstation bias is the standard deviation of the site-specific mean biases, and site-mean RMSE is the arithmetic mean of the site-specific RMSE values, with equal weight assigned to each contributing site.**

| Product           | N   | Bias (95 % CI) (ppm) | Interstation bias (ppm) | RMSE (95 % CI) (ppm) | Site-mean RMSE (ppm) |
|-------------------|-----|----------------------|-------------------------|----------------------|----------------------|
| OCO-2             | 333 | −0.18 [−0.35, 0.00]  | 0.60                    | 1.09 [0.89, 1.31]    | 1.04                 |
| OCO-3             | 495 | 0.08 [−0.10, 0.28]   | 0.56                    | 1.12 [0.98, 1.27]    | 1.12                 |
| GOSAT             | 448 | −0.28 [−0.72, 0.60]  | 1.40                    | 1.45 [1.21, 1.85]    | 1.60                 |
| GOSAT-2 original  | 880 | 3.56 [3.24, 3.88]    | 1.19                    | 3.98 [3.75, 4.27]    | 4.03                 |
| GOSAT-2 corrected | 880 | 0.01 [−0.20, 0.26]   | 0.97                    | 1.54 [1.33, 1.81]    | 1.70                 |
| DQ-1              | 166 | 0.21 [−0.08, 0.48]   | 0.73                    | 1.49 [1.25, 1.74]    | 1.40                 |

**Table S3. Pairwise consistency statistics for satellite XCO<sub>2</sub> products before and after CAMS-based column-definition correction over the selected comparison regions. Bias is defined as the y-axis product minus the x-axis product.**

| Y-axis product      | X-axis product      | Surface type | N    | Before correction |            |            | After correction |            |            |
|---------------------|---------------------|--------------|------|-------------------|------------|------------|------------------|------------|------------|
|                     |                     |              |      | R                 | Bias (ppm) | RMSE (ppm) | R                | Bias (ppm) | RMSE (ppm) |
| DQ-1                | OCO-2               | Land         | 1559 | 0.93              | 0.92       | 1.54       | 0.93             | 0.45       | 1.27       |
|                     |                     | Ocean        | 1922 | 0.89              | 0.91       | 1.79       | 0.89             | 0.49       | 1.59       |
| DQ-1                | OCO-3               | Land         | 1099 | 0.92              | 0.51       | 1.38       | 0.92             | 0.06       | 1.26       |
|                     |                     | Ocean        | 628  | 0.87              | 0.81       | 1.87       | 0.86             | 0.38       | 1.71       |
| DQ-1                | GOSAT               | Land         | 80   | 0.91              | 1.97       | 2.30       | 0.90             | 0.76       | 1.47       |
|                     |                     | Ocean        | 79   | 0.77              | 0.01       | 1.86       | 0.76             | -1.39      | 2.30       |
| DQ-1                | GOSAT-2 (original)  | Land         | 569  | 0.87              | -2.18      | 2.80       | 0.87             | -2.66      | 3.19       |
|                     |                     | Ocean        | 479  | 0.83              | -2.87      | 3.41       | 0.82             | -3.36      | 3.84       |
| DQ-1                | GOSAT-2 (corrected) | Land         | 569  | 0.85              | 1.54       | 2.31       | 0.86             | 1.06       | 2.02       |
|                     |                     | Ocean        | 479  | 0.83              | 0.24       | 1.80       | 0.83             | -0.25      | 1.80       |
| OCO-2               | OCO-3               | Land         | 1435 | 0.97              | -0.32      | 0.82       | 0.97             | -0.30      | 0.81       |
|                     |                     | Ocean        | 1203 | 0.99              | -0.09      | 0.45       | 0.99             | -0.08      | 0.45       |
| OCO-2               | GOSAT               | Land         | 86   | 0.94              | 0.58       | 1.14       | 0.94             | 0.08       | 1.03       |
|                     |                     | Ocean        | 96   | 0.93              | -0.69      | 1.23       | 0.94             | -1.34      | 1.66       |
| OCO-2               | GOSAT-2 (original)  | Land         | 754  | 0.91              | -3.42      | 3.78       | 0.91             | -3.48      | 3.82       |
|                     |                     | Ocean        | 667  | 0.94              | -3.69      | 3.92       | 0.94             | -3.75      | 3.97       |
| OCO-2               | GOSAT-2 (corrected) | Land         | 754  | 0.91              | 0.23       | 1.45       | 0.91             | 0.17       | 1.45       |
|                     |                     | Ocean        | 667  | 0.95              | -0.57      | 1.24       | 0.95             | -0.63      | 1.24       |
| OCO-3               | GOSAT               | Land         | 63   | 0.92              | 1.29       | 1.72       | 0.91             | 0.76       | 1.38       |
|                     |                     | Ocean        | 49   | 0.92              | -0.62      | 1.27       | 0.93             | -1.27      | 1.64       |
| OCO-3               | GOSAT-2 (original)  | Land         | 534  | 0.93              | -2.85      | 3.24       | 0.93             | -2.90      | 3.29       |
|                     |                     | Ocean        | 307  | 0.91              | -3.63      | 3.91       | 0.92             | -3.70      | 3.97       |
| OCO-3               | GOSAT-2 (corrected) | Land         | 534  | 0.92              | 0.77       | 1.58       | 0.92             | 0.72       | 1.57       |
|                     |                     | Ocean        | 307  | 0.94              | -0.42      | 1.18       | 0.94             | -0.49      | 1.20       |
| GOSAT-2 (original)  | GOSAT               | Land         | 122  | 0.89              | 5.09       | 5.32       | 0.88             | 4.68       | 4.94       |
|                     |                     | Ocean        | 61   | 0.95              | 3.28       | 3.45       | 0.95             | 2.79       | 2.99       |
| GOSAT-2 (corrected) | GOSAT               | Land         | 122  | 0.90              | 1.04       | 1.74       | 0.89             | 0.63       | 1.54       |
|                     |                     | Ocean        | 61   | 0.91              | 0.02       | 1.26       | 0.91             | -0.46      | 1.32       |

**Table S4. Regional and surface-type grid-cell statistics, MODIS Band 6 reflectance, and ERA5 10 m wind speed for the DQ-1–OCO-2 and DQ-1–OCO-3 comparisons.**

| Region             | Pair       | Mean grid-cell<br>Band 6 reflectance | Mean 10 m wind<br>speed (m s <sup>-1</sup> ) | Mean grid-cell<br>bias (ppm) | Median grid-cell<br>bias (ppm) | Mean grid-cell<br>RMSE (ppm) |
|--------------------|------------|--------------------------------------|----------------------------------------------|------------------------------|--------------------------------|------------------------------|
| Australia          | DQ-1–OCO-2 | 0.3306                               | —                                            | +0.76                        | +0.72                          | 1.17                         |
|                    | DQ-1–OCO-3 | 0.3270                               | —                                            | +0.57                        | +0.48                          | 1.04                         |
| Tropical Pacific   | DQ-1–OCO-2 | 0.0508                               | 6.48                                         | +0.58                        | +0.40                          | 1.27                         |
|                    | DQ-1–OCO-3 | 0.0348                               | 6.73                                         | +0.30                        | +0.28                          | 1.26                         |
| Sahara             | DQ-1–OCO-2 | 0.5834                               | —                                            | +0.51                        | +0.47                          | 1.11                         |
|                    | DQ-1–OCO-3 | 0.5768                               | —                                            | +0.22                        | +0.19                          | 0.96                         |
| All selected land  | DQ-1–OCO-2 | 0.3970                               | —                                            | +0.46                        | +0.46                          | 1.10                         |
|                    | DQ-1–OCO-3 | 0.4007                               | —                                            | +0.15                        | +0.11                          | 1.04                         |
| All selected ocean | DQ-1–OCO-2 | 0.0374                               | 5.93                                         | +0.51                        | +0.36                          | 1.21                         |
|                    | DQ-1–OCO-3 | 0.0313                               | 5.96                                         | +0.40                        | +0.21                          | 1.20                         |

*Note:* Regional statistics were calculated by equally weighting the contributing  $2^\circ \times 2^\circ$  grid cells. MODIS Band 6 reflectance was averaged over grid cells with valid same-day MYD09CMG.061 retrievals. ERA5 10 m wind speed is reported only for the Tropical Pacific and all selected ocean samples. Bias is defined as DQ-1 minus OCO.

**Table S5. Regional daytime statistics relative to CAMS-derived XCO<sub>2</sub> for the DQ-1-OCO-2 and DQ-1-OCO-3 comparisons.**

| Region             | Pair       | DQ-1-CAMS-derived | OCO-CAMS-derived | DQ-1-CAMS-derived | OCO-CAMS-derived |
|--------------------|------------|-------------------|------------------|-------------------|------------------|
|                    |            | XCO <sub>2</sub>  | XCO <sub>2</sub> | XCO <sub>2</sub>  | XCO <sub>2</sub> |
|                    |            | mean bias (ppm)   | mean bias (ppm)  | mean RMSE (ppm)   | mean RMSE (ppm)  |
| Australia          | DQ-1-OCO-2 | +0.22             | -0.53            | 0.63              | 0.80             |
|                    | DQ-1-OCO-3 | +0.23             | -0.35            | 0.56              | 0.69             |
| Tropical Pacific   | DQ-1-OCO-2 | +0.37             | -0.20            | 1.09              | 0.41             |
|                    | DQ-1-OCO-3 | +0.05             | -0.25            | 1.08              | 0.42             |
| Sahara             | DQ-1-OCO-2 | +0.16             | -0.36            | 0.51              | 0.80             |
|                    | DQ-1-OCO-3 | +0.22             | +0.00            | 0.60              | 0.62             |
| All selected land  | DQ-1-OCO-2 | +0.16             | -0.29            | 0.58              | 0.79             |
|                    | DQ-1-OCO-3 | +0.18             | +0.03            | 0.60              | 0.71             |
| All selected ocean | DQ-1-OCO-2 | +0.37             | -0.14            | 1.00              | 0.45             |
|                    | DQ-1-OCO-3 | +0.29             | -0.11            | 0.96              | 0.43             |

*Note:* Values are equally weighted across contributing  $2^{\circ} \times 2^{\circ}$  grid cells. CAMS-derived XCO<sub>2</sub> is used as a common diagnostic reference rather than as truth. Bias is defined as satellite XCO<sub>2</sub> minus CAMS-derived XCO<sub>2</sub>.