Supplement of

Responses of Arctic black carbon and surface temperature to multi-region emission reductions: a Hemispheric Transport of Air Pollution Phase 2 (HTAP2) ensemble modeling study

Na Zhao et al.

Correspondence to: Kan Huang (huangkan@fudan.edu.cn) and Joshua S. Fu (jsfu@utk.edu)

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S1 Statistical metrics of the model evaluation

The statistical metrics in the present analysis include values of mean bias (MB), mean absolute error (MAE), normalized mean bias (NMB), normalized mean error (NME), and correlative coefficient (R). Detailed equations of the above statistical metrics are shown as follows:

\[ MB = \frac{1}{N} \sum_{i=1}^{N} (C_m - C_o) \]  
(1)

\[ MAE = \frac{1}{N} \sum_{i=1}^{N} |C_m - C_o| \]  
(2)

\[ NMB = \frac{\sum_{i=1}^{N} (C_m - C_o)}{\sum_{i=1}^{N} C_o} \times 100\% \]  
(3)

\[ NME = \frac{\sum_{i=1}^{N} |C_m - C_o|}{\sum_{i=1}^{N} C_o} \times 100\% \]  
(4)

\[ COR = \frac{\sum_{i=1}^{N} (C_m - \bar{C}_m)(C_o - \bar{C}_o)}{\sqrt{\sum_{i=1}^{N} (C_m - \bar{C}_m)^2 \sum_{i=1}^{N} (C_o - \bar{C}_o)^2}} \]  
(5)

Where:

- \( C_m \) = The model-estimated concentration at station i, month j
- \( C_o \) = The observed concentration at station i, month j
- \( \bar{C}_m \) = The average model-estimated concentration of all hours of all sites
- \( \bar{C}_o \) = The average observed concentration of all hours of all sites
- \( N \) = The total numbers of hours of all sites for which the simulations are compared against observations

References

United States Environmental Protection Agency (U.S. EPA). Guidance on the use of models and other analyses for demonstrating attainment of air quality goals for ozone, PM\(_{2.5}\), and regional haze. U.S. Environmental Protection Agency Office of Air Quality Planning and Standards Air Quality Analysis Division Air Quality Modeling Group Research Triangle Park, NC. 2007.

U.S. EPA. Guidance on the Development, Evaluation, and Application of Environmental Models. Council for Regulatory Environmental Modeling U.S. Environmental Protection Agency Washington, DC. 2009.
Figure S1 Four BC monitoring sites (Alert, Barrow, Tiksi, and Zeppelin) in the Arctic Circle.
### (a) Alert

| Parameters | CAMchem | CHASER_re1 | GEOSCHEM | GOCART–v5 | Oslo CTM3–v2 |
|------------|---------|------------|----------|-----------|--------------|
| COR<sup>a</sup> |         | 0.81       | 0.80     | 0.86      | 0.65         |
|            | CAMchem | –          |          |           |              |
|            | CHASER_re1 | 0.81       | –        | 0.61      | 0.70         |
|            | GEOSCHEM | 0.80       | 0.61     | –         | 0.98         |
|            | GOCART–v5 | 0.86       | 0.70     | 0.98      | –            |
|            | Oslo CTM3–v2 | 0.65       | 0.86     | 0.44      | 0.48         |
| NMB<sup>b</sup> (%) |         | –92.99     | –74.12   | –81.17    | 97.44        |
|            | CAMchem | –          | 1642.07  | 346.18    | 217.66       |
|            | CHASER_re1 | –          | 346.18   | –         | 270.08       |
|            | GEOSCHEM | 370.56     | –        | 40.04     | –            |
|            | GOCART–v5 | 562.46     | –        | 40.04     | –            |
|            | Oslo CTM3–v2 | –33.38    | –96.10   | –82.90    | –75.57       |
| NME<sup>c</sup> (%) |         | 92.99      | 74.12    | 81.17     | 106.21       |
|            | CAMchem | –          | 1642.07  | 346.18    | 217.66       |
|            | CHASER_re1 | –          | 346.18   | –         | 270.08       |
|            | GEOSCHEM | 370.56     | –        | 40.04     | –            |
|            | GOCART–v5 | 562.46     | –        | 40.04     | –            |
|            | Oslo CTM3–v2 | 45.70     | 96.10    | 82.90     | 87.57        |
| MB<sup>d</sup> (ng m<sup>–3</sup>) |         | –34.74     | –7.03    | –11.63    | 1.07          |
|            | CAMchem | –          | 34.74    | 27.71     | 23.12        |
|            | CHASER_re1 | 34.74     | –        | 27.71     | 23.12        |
|            | GEOSCHEM | 7.03       | –        | –4.59     | 8.10         |
|            | GOCART–v5 | 11.63      | –        | 4.59      | –            |
|            | Oslo CTM3–v2 | 1.07      | –35.81   | –8.10     | –12.69       |
| MAE<sup>e</sup> (ng m<sup>–3</sup>) |         | 34.74     | 7.03     | 11.63     | 1.22          |
|            | CAMchem | –          | 34.74    | 27.71     | 23.12        |
|            | CHASER_re1 | 34.74     | –        | 27.71     | 23.12        |
|            | GEOSCHEM | 7.03       | –        | 4.59      | 8.10         |
|            | GOCART–v5 | 11.63      | –        | 4.59      | –            |
|            | Oslo CTM3–v2 | 1.22      | 35.81    | 8.10      | 12.69        |

### (b) Barrow

| Parameters | CAMchem | CHASER_re1 | GEOSCHEM | GOCART–v5 | Oslo CTM3–v2 |
|------------|---------|------------|----------|-----------|--------------|
| COR<sup>a</sup> |         | 0.91       | 0.90     | 0.89      | 0.84         |
|            | CAMchem | –          |          |           |              |
|            | CHASER_re1 | 0.91       | –        | 0.82      | 0.79         |
|            | GEOSCHEM | 0.90       | 0.82     | –         | 0.90         |
|            | GOCART–v5 | 0.89       | 0.79     | 0.90      | –            |
|            | Oslo CTM3–v2 | 0.84      | 0.81     | 0.92      | 0.71         |
| NMB<sup>b</sup> (%) |         | –75.42     | –3.89    | –34.61    | 137.53       |
|            | CAMchem | –          | 399.17   | 310.46    | 188.49       |
|            | CHASER_re1 | 399.17    | –        | 310.46    | 188.49       |
|            | GEOSCHEM | 49.47      | –        | –26.62    | 165.92       |
| Parameters | CAMchem | CHASER_re1 | GEOSCHEM | GOCART–v5 | Oslo CTM3–v2 |
|------------|---------|------------|----------|-----------|--------------|
| COR\(^a\)  | CAMchem | –          | 0.45     | 0.47      | 0.33         | 0.54         |
|            | CHASER_re1 | 0.45      | –        | 0.78      | 0.77         | 0.64         |
|            | GEOSCHEM | 0.47      | 0.78     | –         | 0.93         | 0.87         |
|            | GOCART–v5 | 0.33      | 0.77     | 0.93      | –            | 0.75         |
|            | Oslo CTM3–v2 | 0.54    | 0.64     | 0.87      | 0.75         | –            |
| NMB\(^b\) (%) | CAMchem | –          | –184.42  | –35.64    | –46.60       | 11.07        |
|            | CHASER_re1 | 813.44    | –        | 310.05    | 240.81       | 633.13       |
|            | GEOSCHEM | 186.23    | –70.09   | –         | -10.18       | 98.37        |
|            | GOCART–v5 | 200.57    | –67.11   | 18.35     | –            | 121.63       |
|            | Oslo CTM3–v2 | 37.84 | –84.35   | –40.00    | –50.66       | –            |
| NME\(^c\) (%) | CAMchem | –          | 84.42    | 54.38     | 57.93        | 60.09        |
|            | CHASER_re1 | 813.44    | –        | 310.05    | 240.81       | 633.13       |
|            | GEOSCHEM | 186.23    | 70.09    | –         | 20.065       | 104.94       |
|            | GOCART–v5 | 209.03    | 67.11    | 26.28     | –            | 121.63       |
|            | Oslo CTM3–v2 | 67.46 | 84.35    | 50.86     | 50.66        | –            |
| MB\(^d\) (ng m\(^{-3}\)) | CAMchem | –          | –37.12   | –6.99     | –7.66        | 0.12         |
|            | CHASER_re1 | 37.12     | –        | 30.14     | 29.46        | 37.24        |
|            | GEOSCHEM | 6.99      | –30.14   | –         | –0.68        | 7.10         |
|            | GOCART–v5 | 7.66      | –29.46   | 0.68      | –            | 7.78         |
|            | Oslo CTM3–v2 | –0.12  | –37.24   | –7.10     | –7.78        | –            |
| MAE\(^e\) (ng m\(^{-3}\)) | CAMchem | –          | 37.12    | 7.55      | 8.94         | 4.10         |
|            | CHASER_re1 | 37.12     | –        | 30.14     | 29.46        | 37.24        |
| Parameters | CAMchem | CHASER_re1 | GEOSCHEM | GOCART–v5 | Oslo CTM3–v2 |
|------------|---------|------------|----------|----------|-------------|
| COR<sup>a</sup> |         |           |          |          |             |
| CAMchem    | –       | 0.72      | 0.88     | 0.93     | 0.57        |
| CHASER_re1 | 0.72    | –         | 0.51     | 0.72     | 0.61        |
| GEOSCHEM   | 0.88    | 0.51      | –        | 0.92     | 0.57        |
| GOCART–v5  | 0.93    | 0.72      | 0.92     | –        | 0.76        |
| Oslo CTM3–v2 | 0.57  | 0.61      | 0.57     | 0.76     | –           |
| NMB<sup>b</sup> (%) |         |           |          |          |             |
| CAMchem    | –       | –92.52    | –66.10   | –77.05   | 61.88       |
| CHASER_re1 | 1116.80 | –         | 310.46   | 167.04   | 1389.68     |
| GEOSCHEM   | 230.01  | –65.56    | –        | –29.68   | 408.70      |
| GOCART–v5  | 378.64  | –53.57    | 50.21    | –        | 520.07      |
| Oslo CTM3–v2 | 44.23| –87.53    | –58.64   | –73.17   | –           |
| NME<sup>c</sup> (%) |         |           |          |          |             |
| CAMchem    | –       | 89.52     | 66.10    | 77.05    | 108.27      |
| CHASER_re1 | 1116.80 | –         | 310.46   | 167.04   | 1389.68     |
| GEOSCHEM   | 230.01  | 65.56     | –        | 32.28    | 408.70      |
| GOCART–v5  | 378.64  | 53.57     | 52.47    | –        | 520.07      |
| Oslo CTM3–v2 | 81.19| 87.53     | 58.64    | 73.17    | –           |
| MB<sup>d</sup> (ng m<sup>–3</sup>) |         |           |          |          |             |
| CAMchem    | –       | –27.11    | –6.81    | –10.72   | –0.48       |
| CHASER_re1 | 27.11   | –         | 20.30    | 16.40    | 26.63       |
| GEOSCHEM   | 6.81    | –20.30    | –        | –3.91    | 6.33        |
| GOCART–v5  | 10.72   | –16.40    | 3.91     | –        | 10.24       |
| Oslo CTM3–v2 | 0.48 | –26.63    | –6.33    | –10.24   | –           |
| MAE<sup>e</sup> (ng m<sup>–3</sup>) |         |           |          |          |             |
| CAMchem    | –       | 27.11     | 6.81     | 10.72    | 1.84        |
| CHASER_re1 | 27.11   | –         | 20.30    | 16.40    | 26.63       |
| GEOSCHEM   | 6.81    | 20.30     | –        | 4.27     | 6.33        |
| GOCART–v5  | 10.72   | 16.40     | 4.27     | –        | 10.24       |
| Oslo CTM3–v2 | 1.84 | 26.63     | 6.33     | 10.24    | –           |

<sup>a</sup> Correlative coefficient. <sup>b</sup> Normalized mean bias. <sup>c</sup> Normalized mean error. <sup>d</sup> Mean bias. <sup>e</sup> Mean absolute error.
(a) Observation of BC concentrations (μg m⁻³)

- pink: observation
- green: CAMchem
- red dashed: CHASER_re1
- yellow: GEOSCHEMADJOINT
- blue dashed: GOCART-v5
- black dashed: Oslo CTM3-v2
- light blue: average of models

Alert

Barrow

Tiksi

Zeppelin

BC concentrations (μg m⁻³)

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
**Figure S2** (a) Temporal variations in simulated (BASE scenario) and observed BC concentrations near surface at Alert, Barrow, Tiks, and Zeppelin in 2010. (b) Comparison between the vertical profiles of simulated (BASE simulation) and observed BC concentrations (HIPPO) during 24 March–16 April 2010.

**Figure S3.** Spatial distribution of monthly BC emissions in 2010.
(a) CAMchem – summer

(b) CAMchem – winter

(c) CHASER_re1 – summer

(d) CHASER_re1 – winter

(e) GEOS-chem – summer

(f) GEOS-chem – winter
Figure S4. Spatial distributions of BC concentrations for each model in different seasons (summer and winter) in the Arctic near surface in 2010.
Figure S5. Monthly mean reduced (a) dry and (b) wet depositions of the near surface Arctic BC due to 20% emission reductions of six source regions in 2010.
Figure S6. Monthly reduced concentrations of the near-surface Arctic BC due to 20% emission reductions from six source regions for each model in 2010.
Table S2 The vertical stratification unified according to the pressure of CHASER_re1

| The unified layers of this study | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|----------------------------------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|
| Pressure (kPa)                   | > | 97–| 92–| 85–| 78–| 68–| 60–| 52–| 45–| 39– | 34– | 30– | 26– | 23– | 20– | 17– | 15– | 13– | 11.5–| 10– | <10 |
|                                 | 99.5| 99.5| 97 | 92 | 85 | 78 | 68 | 60 | 52 | 45  | 39  | 34  | 30  | 26  | 23  | 20  | 17  | 15  | 13  | 11.5 | 10  | <10 |
| The original layers of          |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |
| participating models            |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |
| CAMchem                         | 1 | 2–3| 4–6| 7– | 12–| 15–| 19–| 21–| 23–| 25– | 27  | 28  | 29  | 30  | 31  | 32  | 33  | 34  | 35  | 36– | 56  |
| CHASER_re1                      | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  | 21– | 32  |
| GEOSCHEM                        | 1–2 | 3 | 4–7 | 8– | 12–| 16–| 20–| 22–| 24–| 26  | 27  | 28  | 29  | 30  | 31  | 32  | 33  | 34  | 35  | 36– | 47  |
| GOCART–v5                       | 1 | 2–3| 4–6| 7– | 12–| 15–| 19–| 21–| 23–| 25– | 27  | 28  | 29  | 30  | 31  | 32  | 33  | 34  | 35  | 36– | 72  |
| OsloCTM3–v2                     | 1–2 | 3–5| 6– | 10–| 13–| 15–| 18–| 20–| 22–| 24– | 25– | 27  | 28  | 29  | 30  | 32  | 33  | 34  | 35  | 36– | 60  |

*There was no pressure in CAMchem, GEOSCHEM, and GOCART–v5 corresponding to the pressure range of 23–26, 13–15, and 23–26 kPa in CHASER_re1, respectively. The BC concentrations were calculated from the average of concentrations of two adjacent layers.*
Figure S7. Reduced dry and wet depositions of the near surface Northern Hemisphere BC due to 20% emission reductions from six source regions during summer and winter in 2010.
Figure S8. Contributions of 20% emission perturbation in SAS to BC concentrations of Arctic in different latitude bands varies with altitude in (a) summer and (b) winter in 2010.