Supplement of

Impact of 2050 climate change on North American wildfire: consequences for ozone air quality

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Figure S1. Monthly Drought Code values in each boreal ecoregion for 1980-2009. Higher values indicate drier conditions.
Figure S2. Cumulative probability of Drought Code (DC) values in boreal ecoregions in Canada and Alaska. Each point represents DC in one ecoregion on one day of fire season (May-October) for 1980-2009. Higher values indicate drier conditions. Dashed lines represent cumulative probability of 15%, 35%, 65%, and 85%. Red points denote the average DCs in the five probability intervals.
Table S1. List of 13 climate models whose meteorological fields are utilized in the projection of area burned in Alaska and Canada.

| Model name                  | Resolution          | Country   |
|-----------------------------|---------------------|-----------|
| CCCMA-CGCM3.1 (T47)         | 3.75° × 3.75°       | Canada    |
| CCCMA-CGCM3.1 (T63)         | 2.8125° × 2.8125°   | Canada    |
| CNRM-CM3                    | 2.8125° × 2.8125°   | France    |
| CSIRO-MK3.0                 | 1.875° × 1.875°     | Australia |
| CSIRO-MK3.5                 | 1.875° × 1.875°     | Australia |
| GFDL-CM2.0                  | 2.5° × 2.0°         | USA       |
| GFDL-CM2.1                  | 2.5° × 2.0°         | USA       |
| GISS-AOM                    | 4.0° × 3.0°         | USA       |
| IAP-FGOALS1.0               | 2.8125° × 3.0°      | China     |
| INGV-ECHAM4                 | 1.125° × 1.125°     | Italy     |
| IPSL-CM4                    | 3.75° × 2.5°        | France    |
| MPI-ECHAM5                  | 1.875° × 1.875°     | Germany   |
| MRI-CGCM2.3.2               | 2.8125° × 2.8125°   | Japan     |
Table S2. Summary of Fire Behavior Prediction (FBP) fuel consumption at five moisture states with CONSUME-python.

| FBP Fuelbed | FBP Fuelbed Name                          | FCCS Fuelbed | Total fuel consumption (kg DM m\(^2\)) |
|-------------|------------------------------------------|--------------|---------------------------------------|
|             |                                          |              | Extra dry | Dry | Moderately dry | Moist | Wet |
| C1          | Spruce-Lichen Woodland                   | 85           | 7.29      | 6.5 | 4.8            | 1.36  | 1.06 |
| C2          | Boreal Spruce                            | 87           | 15.58     | 14.19 | 11.29       | 3.8 | 1.3  |
| C3          | Mature Jack or Lodgepole Pine            | 146          | 7.08      | 6.38 | 4.95          | 2.29 | 1.89 |
| C4          | Immature Jack or Lodgepole Pine          | 148          | 5.79      | 5.28 | 4.4           | 3.42 | 2.56 |
| C5          | Red and White Pine                       | 138          | 8.83      | 7.87 | 6.07          | 3.52 | 2.61 |
| C6          | Conifer Plantation                       | 4            | 9.92      | 9.28 | 8.03          | 6.26 | 3.7  |
| C7          | Ponderosa Pine                           | 67           | 7.02      | 6.31 | 5.07          | 3.24 | 2.28 |
| D1          | Leafless Aspen                           | 142          | 7.42      | 6.49 | 4.9           | 2.82 | 1.89 |
| M1-M2       | Boreal Mixed wood                        | 92           | 3.61      | 3.29 | 2.7           | 1.95 | 1.39 |
| O1          | Grass in Canada                          | 99           | 1.38      | 1.38 | 1.38          | 1.25 | 1.13 |
| O1a-O1b     | Grass in Alaska                          | 98           | 0.85      | 0.82 | 0.77          | 0.54 | 0.32 |
| Tundra      | Tundra                                   | 97           | 1.7       | 1.7  | 1.67          | 1.28 | 0.92 |

FCCS: Fuel Characteristic Classification System (FCCS)
DM: dry matter
**Table S3.** Summary of reported NO\(_x\) emission factors for forests in the western U.S.

| Reference               | Location        | Fuel type               | Emission factor \(^a\) |
|-------------------------|-----------------|-------------------------|-------------------------|
| Hegg et al. (1990)      | Oregon          | Pine                    | 2.54                    |
| Hegg et al. (1990)      | Oregon          | Douglass Fir            | 0.81                    |
| Laursen et al. (1992)   | Montana         | Debris from Pine        | 1.8                     |
| EPA (1995)              | Inventory       | Boreal and coniferous   | 2                       |
| Yokelson et al. (1996)  | Lab             | Pine                    | 2.5                     |
| Hobbs et al. (1996)     | Pacific Northwest |                        | 3.7                     |
| **Average (used in this study)** |                |                          | **2.2 \(^b\)** |

\(^a\) units: g NO\(_x\) kg DM\(^{-1}\), DM is dry matter.

\(^b\) 1.6 g NO kg DM\(^{-1}\), assuming 70% NO\(_2\)
### Table S4. Changes of meteorological variables at midcentury, and their contributions to the predicted changes in area burned for different boreal ecoregions.

| Ecoregions            | Simulated Median Mean | # of models (p<0.05) | Changes in Reg. terms | Percent Contribution |
|-----------------------|-----------------------|----------------------|-----------------------|---------------------|
|                       | 1983-1999 | 2048-2064 |                      |                      |
| Alaska Boreal Interior|           |           |                      |                      |
| T\textsubscript{max}-SUM (°C) | 19.9     | 21.5     | 10 | 4.7 \times 10^5 | 67 |
| HGT.SUM(-1) (m)       | 5585     | 5625     | 13 | 2.0 \times 10^5 | 28 |
| ISI\textsubscript{max}(-1) | 7.0     | 7.4      | 1  | -0.3 \times 10^5 | 5  |
| Alaska Boreal Cordillera|          |           |                      |                      |
| HGT.SUM (m)           | 5597     | 5637     | 13 | 3.0 \times 10^5 | 61 |
| T\textsubscript{max}-AUT(-2) (°C) | 1.1     | 3.3      | 13 | 0.7 \times 10^5 | 15 |
| T.SPR (°C)            | 0        | 2.2      | 11 | 1.1 \times 10^5 | 24 |
| Taiga Cordillera      |           |           |                      |                      |
| T\textsubscript{max}-ANN(-2) (°C) | -3.7    | -1.6     | 13 | 1.1 \times 10^5 | 47 |
| HGT.SUM (m)           | 5612     | 5646     | 13 | 1.3 \times 10^5 | 53 |
| Canadian Boreal Cordillera|        |           |                      |                      |
| HGT.SUM (m)           | 5629     | 5667     | 13 | 2.8 \times 10^5 | 100 |
| Western Cordillera    |           |           |                      |                      |
| T\textsubscript{max}-SUM (°C) | 24.5     | 26.9     | 13 | 0.5 \times 10^5 | 74 |
| HGT.SPR (m)           | 5512     | 5540     | 12 | -0.1 \times 10^5 | 16 |
| DMC\textsubscript{max}(-1) | 75.7    | 65.4     | 5  | 0.1 \times 10^5 | 10 |
| Taiga Plain           |           |           |                      |                      |
| ISI                   | 1.7      | 1.7      | 2  | -2 \times 10^5 | 52 |
| Prec.FS(-1) (mm day\textsuperscript{-1}) | 1.3     | 1.4      | 6  | -0.7 \times 10^5 | 18 |
| Prec.Win (mm day\textsuperscript{-1}) | 0.5     | 0.6      | 8  | -1.2 \times 10^5 | 30 |
| Boreal Plain          |           |           |                      |                      |
| DSR\textsubscript{max} | 5.5      | 6.0      | 2  | -0.2 \times 10^5 | 10 |
| RH.SUM(-2) (%)        | 65.5     | 67.1     | 4  | 1.4 \times 10^5 | 80 |
| FWI\textsubscript{max}(-1) | 19.9    | 19.9     | 2  | -0.2 \times 10^5 | 10 |
| Western Taiga Shield  |           |           |                      |                      |
| ISI\textsubscript{max} | 9.3      | 9.1      | 2  | -2.9 \times 10^5 | 51 |
| Variable                  | RH.AUT (%) | Eastern Taiga Shield | RH.WIN(-2) (%) | RH.ANN (%) | DMC_{\text{max}}(-2) | Hudson Plain      | Western Mixed Wood Shield | Eastern Mixed Wood Shield |
|---------------------------|------------|----------------------|---------------|------------|----------------------|----------------------|---------------------------|--------------------------|
|                           |            |                      |               |            |                      |                     |                           |                          |
| RH.AUT (%)                | 80.6       | 81.7                 | 6             | 2.8 \times 10^5 | 49                   |                     |                           |                          |
| Eastern Taiga Shield      |            |                      |               |            |                      |                     |                           |                          |
| RH.WIN(-2) (%)            | 71.6       | 72.8                 | 6             | 7.0 \times 10^4 | 40                   |                     |                           |                          |
| RH.ANN (%)                | 73.7       | 74.3                 | 6             | -2.9 \times 10^4 | 17                   |                     |                           |                          |
| DMC_{\text{max}}(-2)     | 27.6       | 35.4                 | 4             | -7.4 \times 10^4 | 43                   |                     |                           |                          |
| Hudson Plain              |            |                      |               |            |                      |                     |                           |                          |
| HGT.SUM (m)               | 5640       | 5692                 | 13            | 1.4 \times 10^5 | 52                   |                     |                           |                          |
| T.SPR (°C)                | -10.1      | -7.5                 | 12            | -0.6 \times 10^5 | 25                   |                     |                           |                          |
| T_{\text{max}}.WIN(-1) (°C) | -19.3     | -15.1                | 13            | -0.6 \times 10^5 | 23                   |                     |                           |                          |
| Western Mixed Wood Shield |            |                      |               |            |                      |                     |                           |                          |
| BUI_{\text{max}}         | 64.2       | 66.7                 | 3             | 0.4 \times 10^5 | 10                   |                     |                           |                          |
| HGT.SUM (m)               | 5672       | 5721                 | 13            | 3.9 \times 10^5 | 90                   |                     |                           |                          |
| Eastern Mixed Wood Shield |            |                      |               |            |                      |                     |                           |                          |
| RH.SUM (%)                | 73.7       | 73.5                 | 2             | 0          | 2                    |                     |                           |                          |
| HGT.AUT(-1) (m)           | 5519       | 5564                 | 13            | 1.6 \times 10^5 | 98                   |                     |                           |                          |

\(a\) Number of models out of the 13 that predict significant (p<0.05) changes in meteorological variables in each ecoregion, as determined by the Student t-test. If the median value of the change is positive, only those predicting a significant increase are counted and vice versa for a negative change.

\(b\) Results are calculated as the changes in variables multiplied by the regression coefficients for the median models. A median model is defined as the model that predicts median ratios of the area burned in a specific ecoregion as shown in Table 3.

\(c\) Percent contributions of the absolute changes in individual regression terms to their sum for the median models.
| Incidence/Location               | Period                  | Fuel load method                                      | Fuel consumption method                        | Fuel consumption $^a$          | Reference                |
|---------------------------------|-------------------------|------------------------------------------------------|------------------------------------------------|-------------------------------|--------------------------|
| **Alaska**                      |                         |                                                      |                                                |                               |                          |
| Hajdukovich Creek               | June, 1994              | remotely sensed vegetation classes with field data   | remotely sensed burning severity with field data| 8.0 (3.2 to 21.6) $^b$        | Michalek et al. (2000)    |
| Alaskan Yukon River Basin       | 2004                    | FCCS inventory data                                  | derived from literature                         | 6.2                           | Tan et al. (2007)         |
| Boundary Fire                   | 2004                    | FCCS or results from different models modeled with parameters from field data | six different models with different moisture states | 2.7 to 12.2 $^c$             | French et al. (2011)     |
| Alaskan boreal forest           | 1990-1991               | forest and soil inventory (Kasischke et al., 1995)  | ecoregion-level estimates from field data       | 4.0 (3.2 to 5.8) $^d$         | Kasischke et al. (1995)  |
| Alaskan boreal forest           | 1950-1999               | field inventory data                                 | pre-fire and post-fire soil and stand data      | 6.6 (3.0 to 9.2) $^d$         | French et al. (2003)     |
| Alaskan black spruce            | 2004                    | national inventory data for fuel types               | power-law relations between depth and carbon loss pre-fire and post-fire soil and stand data | 5.9 (early season) 12.3 (late season) | Boby et al. (2010)       |
| Interior Alaska                 | Summer, 2004            | N/A                                                  | Empirical functions based on observations       | 3.0 to 6.0 $^d$               | Turetsky et al. (2011)   |
| Interior Alaska                 | 2004, 2006-2008         | remotely sensed vegetation and fire perimeters      | derived from literature                         | 3.8                           | Kasischke and Hoy (2012) |
| Alaska                          | 1960-2000               | N/A                                                  | GFED v3.1                                       | 4.0                           | Schultz et al. (2008)    |
| Alaska                          | 1997-2009               | GFED v3.1                                            | CONSUME-python                                   | 3.1 (entire) 5.5 (interior)   | van der Werf et al. (2010) |
| Alaska                          | 1980-2009               | Canadian FBP System with projection to FCCS          |                                                |                               | This study               |
| *Canada*                        |                         |                                                      |                                                |                               |                          |
| Montreal Lake fire, Saskatchewan| 2003                    | Canadian FBP System                                  | Canadian FBP System                              | 0.3 to 6.7 $^b$               | de Groot et al. (2007)   |
| Montreal Lake fire, Saskatchewan| 2003                    | CBM-CFS3 model                                       | BIOFIRE model                                   | 0.3 to 6.0 $^b$               | de Groot et al. (2007)   |
| Montreal Lake Fire, Saskatchewan| 2003                    | national forest inventory or FCCS                    | six different models with different moisture states | 1.6 to 13.0 $^c$             | French et al. (2011)     |
| Region          | Period     | Source              | Method                          | Value          | Reference                          |
|-----------------|------------|---------------------|---------------------------------|----------------|------------------------------------|
| Canadian peatland | March, 1999 | N/A                 | based on ash content in upper and deeper peat layers | 4.4 ± 1.0 g | Turetsky and Wieder (2001)         |
| Canada          | 1960-2000  | N/A                 | derived from literatures         | 2.6            | Schultz et al. (2008)              |
| Canada          | 1997-2009  | GFED v3.1           | GFED v3.1                        | 3.7            | van der Werf et al. (2010)         |
| Canada          | 1980-2009  | Canadian FBP System with projection to FCCS | CONSUME-python | 3.5 (1.8 to 7.2) | This study                        |

a Fuel consumption unit is kg DM m$^{-2}$ burned. For some studies that use units of kg C m$^{-2}$ burned, we multiply the reported values by 2 g DM g$^{-1}$ C.

b Range indicates values for different fuel types.

c Range indicates values for different models.

d Range indicates values for different years or fires with different size of area burned.

e Range indicates values for different facing slopes.

f Range indicates values for different ecoregions.

g Range indicates the uncertainties for the estimates.
Reference:
Amiro, B. D., Todd, J. B., Wotton, B. M., Logan, K. A., Flannigan, M. D., Stocks, B. J.,
Mason, J. A., Martell, D. L., and Hirsch, K. G.: Direct carbon emissions from
Canadian forest fires, 1959-1999, Can. J. For. Res., 31, 512-525, doi:10.1139/cjfr-31-
3-512, 2001.
Amiro, B. D., Cantin, A., Flannigan, M. D., and de Groot, W. J.: Future emissions from
Canadian boreal forest fires, Can. J. For. Res., 39, 383-395, doi:10.1139/X08-154,
2009.
Balshi, M. S., McGuire, A. D., Zhuang, Q., Melillo, J., Kicklighter, D. W., Kasischke, E.,
Wirth, C., Flannigan, M., Harden, J., Clein, J. S., Burnside, T. J., McAllister, J., Kurz,
W. A., Apps, M., and Shvidenko, A.: The role of historical fire disturbance in the
carbon dynamics of the pan-boreal region: A process-based analysis, J. Geophys. Res.,
112, doi:10.1029/2006jg000380, 2007.
Boby, L. A., Schuur, E. A. G., Mack, M. C., Verbyla, D., and Johnstone, J. F.: Quantifying fire severity, carbon, and nitrogen emissions in Alaska's boreal forest, Ecological Applications, 20, 1633-1647, 2010.
de Groot, W. J., Landry, R., Kurz, W. A., Anderson, K. R., Englefield, P., Fraser, R. H.,
Hall, R. J., Banfield, E., Raymond, D. A., Decker, V., Lynham, T. J., and Pritchard, J.
M.: Estimating direct carbon emissions from Canadian wildland fires, Int. J. Wildland
Fire, 16, 593-606, doi:10.1071/Wf06150, 2007.
EPA, U. S.: Compilation of Air Pollutant Emission Factors fifth ed., Research Triangle
Park, NC, 1995.
French, N. H. F., Kasischke, E. S., Stocks, B. J., Mudd, J. P., Martell, D. L., and Lee, B.
S.: Carbon release from fires in the North American boreal forest, in: Fire, climate
change, and carbon cycling in the boreal forest, edited by: Kasischke, E. S., and
Stocks, B. J., Springer-Verlag, New York, 377-388, 2000.
French, N. H. F., Kasischke, E. S., and Williams, D. G.: Variability in the emission of
carbon-based trace gases from wildfire in the Alaskan boreal forest, J. Geophys. Res.,
108, 8151, doi:10.1029/2001jd000480, 2003.
French, N. H. F., de Groot, W. J., Jenkins, L. K., Rogers, B. M., Alvarado, E., Amiro, B.,
de Jong, B., Goetz, S., Hoy, E., Hyer, E., Keane, R., Law, B. E., McKenzie, D.,
McNulty, S. G., Ottmar, R., Perez-Salicrup, D. R., Randerson, J., Robertson, K. M., and Turetsky, M.: Model comparisons for estimating carbon emissions from North American wildland fire, J. Geophys. Res., 116, doi:10.1029/2010jg001469, 2011.

Hegg, D. A., Radke, L. F., Hobbs, P. V., Rasmussen, R. A., and Riggen, P. J.: Emissions of Some Trace Gases from Biomass Fires, J. Geophys. Res., 95, 5669-5675, doi:10.1029/Jd095id05p05669, 1990.

Hobbs, P. V., Reid, J. S., Herring, J. A., Nance, J. D., Weiss, R. E., Ross, J. L., Hegg, D. A., Ottmar, R. D., and Lioussse, C.: Particle and trace-gas measurements in smoke from prescribed burns of forest products in the Pacific Northwest, in: Biomass Burning and Global Change, edited by: Levine, J. S., MIT Press, New York, U.S., 697-715, 1996.

Kane, E. S., Kasischke, E. S., Valentine, D. W., Turetsky, M. R., and McGuire, A. D.: Topographic influences on wildfire consumption of soil organic carbon in interior Alaska: Implications for black carbon accumulation, J. Geophys. Res., 112, doi:10.1029/2007jg000458, 2007.

Kasischke, E. S., French, N. H. F., Bourgeauchavez, L. L., and Christensen, N. L.: Estimating Release of Carbon from 1990 and 1991 Forest-Fires in Alaska, J. Geophys. Res., 100, 2941-2951, doi:10.1029/94JD02957, 1995.

Kasischke, E. S., and Hoy, E. E.: Controls on carbon consumption during Alaskan wildland fires, Global Change Biology, 18, 685-699, doi:10.1111/j.1365-2486.2011.02573.x, 2012.

Laursen, K. K., Hobbs, P. V., Radke, L. F., and Rasmussen, R. A.: Some Trace Gas Emissions from North-American Biomass Fires with an Assessment of Regional and Global Fluxes from Biomass Burning, J. Geophys. Res., 97, 20687-20701, doi:10.1029/92JD02168, 1992.

Michalek, J. L., French, N. H. F., Kasischke, E. S., Johnson, R. D., and Colwell, J. E.: Using Landsat TM data to estimate carbon release from burned biomass in an Alaskan spruce forest complex, International Journal of Remote Sensing, 21, 323-338, 2000.

Schultz, M. G., Heil, A., Hoelzemann, J. J., Spessa, A., Thonicke, K., Goldammer, J. G., Held, A. C., Pereira, J. M. C., and van het Bolscher, M.: Global wildland fire
emissions from 1960 to 2000, Global Biogeochemical Cycles, 22, doi:10.1029/2007gb003031, 2008.

Tan, Z., Tieszen, L. L., Zhu, Z., Liu, S., and Howard, S. M.: An estimate of carbon emissions from 2004 wildfires across Alaskan Yukon River Basin, Carbon Balance and Management, 2, doi:10.1186/1750-0680-2-12, 2007.

Turetsky, M. R., and Wieder, R. K.: A direct approach to quantifying organic matter lost as a result of peatland wildfire, Can. J. For. Res., 31, 363-366, 2001.

Turetsky, M. R., Kane, E. S., Harden, J. W., Ottmar, R. D., Manies, K. L., Hoy, E., and Kasischke, E. S.: Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands, Nature Geoscience, 4, 27-31, doi:10.1038/Ngeo1027, 2011.

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009), Atmospheric Chemistry and Physics, 10, 11707-11735, doi:10.5194/Acp-10-11707-2010, 2010.

Yokelson, R. J., Griffith, D. W. T., and Ward, D. E.: Open-path Fourier transform infrared studies of large-scale laboratory biomass fires, J. Geophys. Res., 101, 21067-21080, doi:10.1029/96jd01800, 1996.