Accomplishments of:

IGAC's Tropospheric Ozone Assessment Report

Global metrics for climate change, human health and crop/ecosystem research

Written by the TOAR Steering Committee
September, 2019

Tropospheric Ozone Assessment Report (TOAR): Global metrics for climate change, human health and crop/ecosystem research, is an official Activity of the International Global Atmospheric Chemistry Project (IGAC), approved by the IGAC Scientific Steering Committee on March 13, 2014 (www.igacproject.org/TOAR).

Mission: To provide the research community with an up-to-date scientific assessment of tropospheric ozone's global distribution and trends from the surface to the tropopause.

Goals: 1) Produce the first tropospheric ozone assessment report based on all available surface observations, the peer-reviewed literature and new analyses.

2) Generate easily accessible, documented data on ozone exposure and dose metrics at thousands of measurement sites around the world, freely accessible for research on the global-scale impact of ozone on climate, human health and crop/ecosystem productivity.

Organization: TOAR is a science effort initiated by IGAC, and developed by an international team of experts. TOAR has received basic financial and logistical support from IGAC, the US National Oceanic and Atmospheric Administration (NOAA), Forschungszentrum Jülich, and the World Meteorological Organization (WMO). Costs associated with scientific data analysis, writing of articles, travel to meetings and the organization of meetings were largely covered by the participants.

TOAR has been coordinated by an 11-member Steering Committee (see list of members at the end of this report), which is chaired by Owen Cooper, CIRES, University of Colorado/NOAA ESRL, Boulder, USA.

TOAR established seven regional working groups to gather all available surface ozone time series from around the world, a working group that focused on free troposphere and satellite ozone observations, and a working group on metrics, statistics, and data analysis tools. Writing teams were formed to produce the topical "chapters" of the report. Interactions between these groups and teams are summarized by the work-flow diagram in Figure 1.

I. Accomplishments

In fulfillment of its mission and to complete its two primary goals, TOAR accomplished the following over the period detailed in the TOAR timeline (see Section II):

1) TOAR has published its findings as a series of peer-reviewed manuscripts made available through a Special Feature of the open-access, non-profit journal, *Elementa: Science of the Anthropocene* (https://collections.elementascience.org/toar). Seven TOAR papers have been published so far and they are already being cited at a remarkable rate, as shown in Figure 2 (a total of 194 citations to date). An eighth TOAR paper is *in-press* and the ninth and final paper is in preparation. A list of the TOAR papers is provided at the end of this document.

2) TOAR built the world's largest database of ozone metrics, calculated consistently for over 9000 surface ozone time series worldwide. Created by Forschungszentrum Jülich the database is entirely open-access (https://join.fz-juelich.de/), allowing anyone to download the ozone metrics and conduct their own research. A REST interface has been implemented to allow interoperable machine access to the TOAR Surface Ozone Database, and pre-compiled metrics datasets for easy use were published at the open access PANGAEA archive: https://doi.org/10.1594/PANGAEA.876108. Figures 3 and 4 provide examples of the database's global coverage and its ability to summarize regional ozone trends.

3) Results from the extensive quality control of metadata and data that were included in the TOAR database were reported back to international air quality agencies and research data repositories. In many cases, these reports have led to improvements in the primary data archives.

4) TOAR organized the largest international group of scientists and air quality managers ever assembled for assessing the current state of tropospheric ozone research and observations. TOAR had the participation of over 230 individuals from 36 nations, representing research on all seven continents.

5) TOAR results have been presented at large international conferences, in particular the European Geophysical Union, Vienna, April 2017, American Geophysical Union Fall Meeting, New Orleans, December 2017, the NOAA Global Monitoring Division Annual Meeting, Boulder, 2018, and the IGAC Conference in Takamatsu, Japan, September 2018.

6) Several press releases on TOAR achievements have been picked up by the news media in various countries. In particular, TOAR featured prominently in the 2018 WMO Global Atmosphere Watch Reactive Gases Bulletin: https://library.wmo.int/doc_num.php?explnum_id=5244 Sept. 2018

7) TOAR follows a full open science and open data approach and provides all of its products to the global community free of charge. Due to the copyright policies of the journal, *Elementa*, the authors own the copyright to each paper, and therefore permission can easily be given to other scientists or the public to reproduce the figures free of charge.

8) A measure of TOAR's success is the usage of the TOAR database by the broader research community. In addition to the core TOAR papers, new independent studies are

appearing in the peer-reviewed literature, which have either used ozone metrics from the TOAR database or have reproduced TOAR figures. To date eleven such papers (in addition to the original TOAR papers) have been published, and we expect this number to grow quickly (see list at the end of this document).

9) TOAR's accomplishments have been achieved despite the absence of base funding. Participation by the research community was entirely voluntary. Basic funding for meetings was provided by NOAA, WMO, IGAC, AEMET (Spanish Meteorological Agency), Research Center for Eco-Environmental Sciences at the Chinese Academy of Sciences, Nanjing University, and Forschungszentrum Jülich. The remaining costs for meetings, including registration fees and travel, were covered by the participants. Development of the TOAR database was supported by Forschungszentrum Jülich. Publication fees were kept to a minimum because the Steering Committee negotiated a fixed manuscript publication fee of $1000 per paper, each with a page length up to 50 journal pages. Publication fees were covered by NOAA Chemical Sciences Division, NOAA Geophysicial Fluid Dynamics Laboratory, Air Quality Research Division - Environment and Climate Change Canada, and Forschungszentrum Jülich.

II. Timeline

March 14, 2014: IGAC Scientific Steering Committee approves TOAR as a new IGAC Activity.

December 10-11, 2014: TOAR Workshop 1.01, was held at the NOAA Earth System Research Laboratory, Boulder, to develop TOAR's scope, structure and timeline.

February – March, 2015: Preliminary organization of TOAR author teams and working groups, establishment of TOAR database and initiation of ozone data collection period.

April 28-30, 2015: TOAR Workshop 1.02 was held at the Agencia Estatal de Meteorología (AEMET), Madrid, Spain (co-sponsored by WMO) to develop the report outline.

January 25-27, 2016: TOAR Workshop 1.03 was held at the Xijiao Hotel, Beijing, to review the first draft of the report and develop the second draft.

April 25-29, 2016: TOAR Workshop 1.04 was held in Jülich, Germany, to conduct the Big Data analysis of the TOAR database to supply the figures and analysis for the report.

April 30, 2016: TOAR database freeze date, no further data submissions.

September, 2017: The TOAR database of ozone metrics was made publicly available

October, 2017: Publication of "TOAR Database" in *Elementa*: *Science of the Anthropocene*

September 26-30, 2016: IGAC meeting in Breckenridge, Colorado. TOAR Steering Committee and lead authors met to discuss the second draft.

2017-2019: Submission period of the TOAR papers to the journal, *Elementa*: *Science of the Anthropocene*

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Publications in the TOAR Special Feature of Elementa:

Chang, K.-L., I. Petropavlovskikh, O. R. Cooper, M. G. Schultz and T. Wang (2017), Regional trend analysis of surface ozone observations from monitoring networks in eastern North America, Europe and East Asia, *Elem Sci Anth, 5:50*, DOI: http://doi.org/10.1525/elementa.243

Fleming, Z. L., R. M. Doherty et al. (2018), Tropospheric Ozone Assessment Report: Present-day ozone distribution and trends relevant to human health, *Elem Sci Anth*, *6(1):12*, DOI: https://doi.org/10.1525/elementa.273

Gaudel, A., et al. (2018), Tropospheric Ozone Assessment Report: Present-day distribution and trends of tropospheric ozone relevant to climate and global atmospheric chemistry model evaluation, *Elem Sci Anth, 6(1):39*, DOI: https://doi.org/10.1525/elementa.291

Lefohn, A. S., et al. (2018), Tropospheric ozone assessment report: Global ozone metrics for climate change, human health, and crop/ecosystem research, *Elem Sci Anth, 6(1):28*, DOI: http://doi.org/10.1525/elementa.279

Mills, G, et al. (2018), Tropospheric Ozone Assessment Report: Present-day tropospheric ozone distribution and trends relevant to vegetation. *Elem Sci Anth, 6(1):47*, DOI: https://doi.org/10.1525/elementa.302

Schultz, M. G., S. Schroeder, O. Lyapina and O. R. Cooper, et al. (2017), Tropospheric Ozone Assessment Report: Database and metrics data of global surface ozone observations, *Elem Sci Anth, 5:58*, DOI: http://doi.org/10.1525/elementa.244

Tarasick, D. W., I. E. Galbally, **O. R. Cooper**, M. G. Schultz, G. Ancellet, T. Leblanc, T. J. Wallington, J. Ziemke, X. Liu, M. Steinbacher, J. Staehelin, C. Vigouroux, J. W. Hannigan, O. García, G. Foret, P. Zanis, E. Weatherhead, I. Petropavlovskikh, H. Worden, M. Osman, J. Liu, K.-L. Chang, A. Gaudel, M. Lin, M. Granados-Muñoz, A. M. Thompson, S. J. Oltmans, J. Cuesta, G. Dufour, V. Thouret, B. Hassler, T. Trickl and J. L. Neu (2019), Tropospheric Ozone Assessment Report: Tropospheric ozone observations: Tropospheric ozone from 1877 to 2016, observed levels, trends and uncertainties, *Elementa: Science of the Anthropocene, in-press*

Young, P. J, V. Naik et al. (2018), Tropospheric Ozone Assessment Report: Assessment of global-scale model performance for global and regional ozone distributions, variability, and trends, *Elem Sci Anth, 6(1):10*, DOI: https://doi.org/10.1525/elementa.265

TOAR publications in preparation:

Archibald, A. T., Y. Elshorbany, J. L. Neu, O. Cooper, M. Coyle, R. Derwent, R. Doherty A. Finco, G.J. Frost, I. E. Galbally, G. Gerosa, C. Granier, P. Griffiths, R. Hossaini, L. Hu, A. Lefohn, M. Y. Lin, M. Naja, V. Naik, S. Oltmans, A. Saiz-Lopez, P. Saxena, M. G. Schultz, I. Shahid, D. Shallcross, T. Trickl, T. J. Wallington, T. Wang, O. Wild, H. Worden, P. Young (2019), Tropospheric Ozone Assessment Report: Critical review of the present-day and near-future tropospheric ozone burden and budget, in preparation for submission to *Elem. Sci. Anth*.

Papers that utilize the TOAR database or reproduce TOAR graphics, in addition to the papers in the TOAR Special Feature of Elementa:

2018

Blunden, J., D. S. Arndt, and G. Hartfield, Eds., 2018: State of the Climate in 2017. *Bull. Amer. Meteor. Soc.*, **99** (8), S*i*–S332, doi:10.1175/2018BAMSStateoftheClimate.1.

Jaffe, D. A., Cooper, O. R., Fiore, A. M., Henderson, B.H., Tonneson, G. S., Russell, A. G., et al. (2018), Scientific assessment of background ozone over the U.S.: Implications for air quality management, *Elem. Sci. Anth., 6(1):56*, DOI: http://doi.org/10.1525/elementa.309

Liang, C.-K., West, J. J., Silva, R. A., Bian, H., Chin, M., Davila, Y., Dentener, F. J., Emmons, L., Flemming, J., Folberth, G., Henze, D., Im, U., Jonson, J. E., Keating, T. J., Kucsera, T., Lenzen, A., Lin, M., Lund, M. T., Pan, X., Park, R. J., Pierce, R. B., Sekiya, T., Sudo, K., and Takemura, T.: HTAP2 multi-model estimates of premature human mortality due to intercontinental transport of air pollution and emission sectors, Atmos. Chem. Phys., 18, 10497-10520, https://doi.org/10.5194/acp-18-10497-2018, 2018.

Lu, X., J. Hong, L. Zhang, O. R. Cooper, M. G. Schultz, X. Xu, T. Wang, M. Gao, Y. Zhao, Y. Zhang (2018), Severe surface ozone pollution in China: a global perspective, Environ. Sci. Technol. Lett. 5, 8, 487-494.

Schultz, M. G., Stadtler, S., Schröder, S., Taraborrelli, D., Franco, B., Krefting, J., Henrot, A., Ferrachat, S., Lohmann, U., Neubauer, D., Siegenthaler-Le Drian, C., et al.: The chemistry–climate model ECHAM6.3-HAM2.3-MOZ1.0, Geosci. Model Dev., 11, 1695-1723, https://doi.org/10.5194/gmd-11-1695-2018, 2018.

Stadtler, S., Simpson, D., Schröder, S., Taraborrelli, D., Bott, A., and Schultz, M.: Ozone impacts of gas–aerosol uptake in global chemistry transport models, Atmos. Chem. Phys., 18, 3147-3171, https://doi-org.colorado.idm.oclc.org/10.5194/acp-18-3147-2018, 2018.

Strode, S. A., J. R. Ziemke, L. D. Oman, L. N. Lamsal, M. A. Olsen and J. Liu (2018), Global changes in the diurnal cycle of surface ozone, *Atmos. Environ., 199,* 323-333.

World Meteorological Organization (2018), WMO Reactive Gases Bulletin: Highlights from the Global Atmosphere Watch Programme, No. 2, October, 2018, https://library.wmo.int/index.php?lvl=bulletin_display&id=3959#.XDfFxbx7nRY

WMO (World Meteorological Organization), *Scientific Assessment of Ozone Depletion: 2018*, Global Ozone Research and Monitoring Project–Report No. 58, 588 pp., Geneva, Switzerland, 2018.

2019

Chang, K.-L., Cooper, O. R., West, J. J., Serre, M. L., Schultz, M. G., Lin, M., Marécal, V., Josse, B., Deushi, M., Sudo, K., Liu, J., and Keller, C. A. (2019), A new method (M^3Fusion v1) for combining observations and multiple model output for an improved estimate of the global surface ozone distribution, *Geosci. Model Dev., 12*, 955-978, https://doi.org/10.5194/gmd-12-955-2019.

Cooper, O. R. (2019), Detecting the fingerprints of observed climate change on surface ozone variability, *Science Bulletin*, *64*, 359-360, doi: https://doi.org/10.1016/j.scib.2019.02.013

Shen, L., Jacob, D. J., Liu, X., Huang, G., Li, K., Liao, H., and Wang, T.: An evaluation of the ability of the Ozone Monitoring Instrument (OMI) to observe boundary layer ozone pollution across China: application to 2005–2017 ozone trends, Atmos. Chem. Phys., 19, 6551-6560, https://doi.org/10.5194/acp-19-6551-2019, 2019.

Tarasick, D., I. Galbally, et al. (2019), Tropospheric Ozone Assessment Report: Tropospheric ozone observations - How well can we measure tropospheric ozone today and in the historic past?, *Elem. Sci. Anth., in-review*

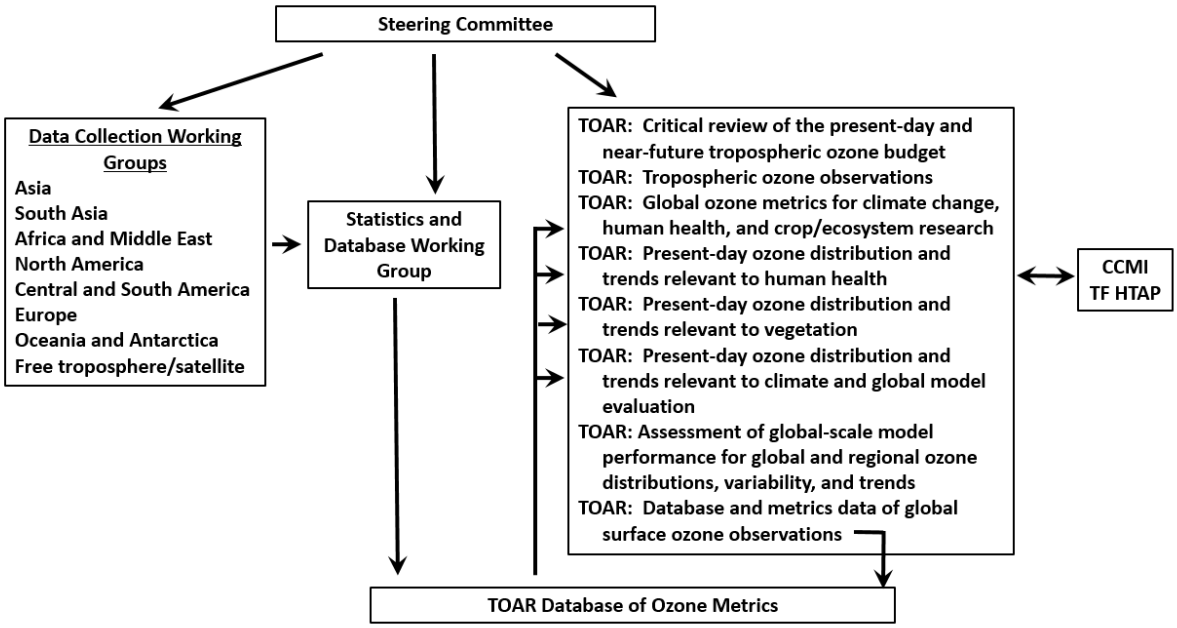

Figure 1. Work flow diagram of the assessment report. TOAR has been designed to collaborate with IGAC's Chemistry Climate Model Initiative (CCMI) and the U.N. Economic Commission for Europe Task Force on Hemispheric Transport of Air Pollution (TF HTAP).

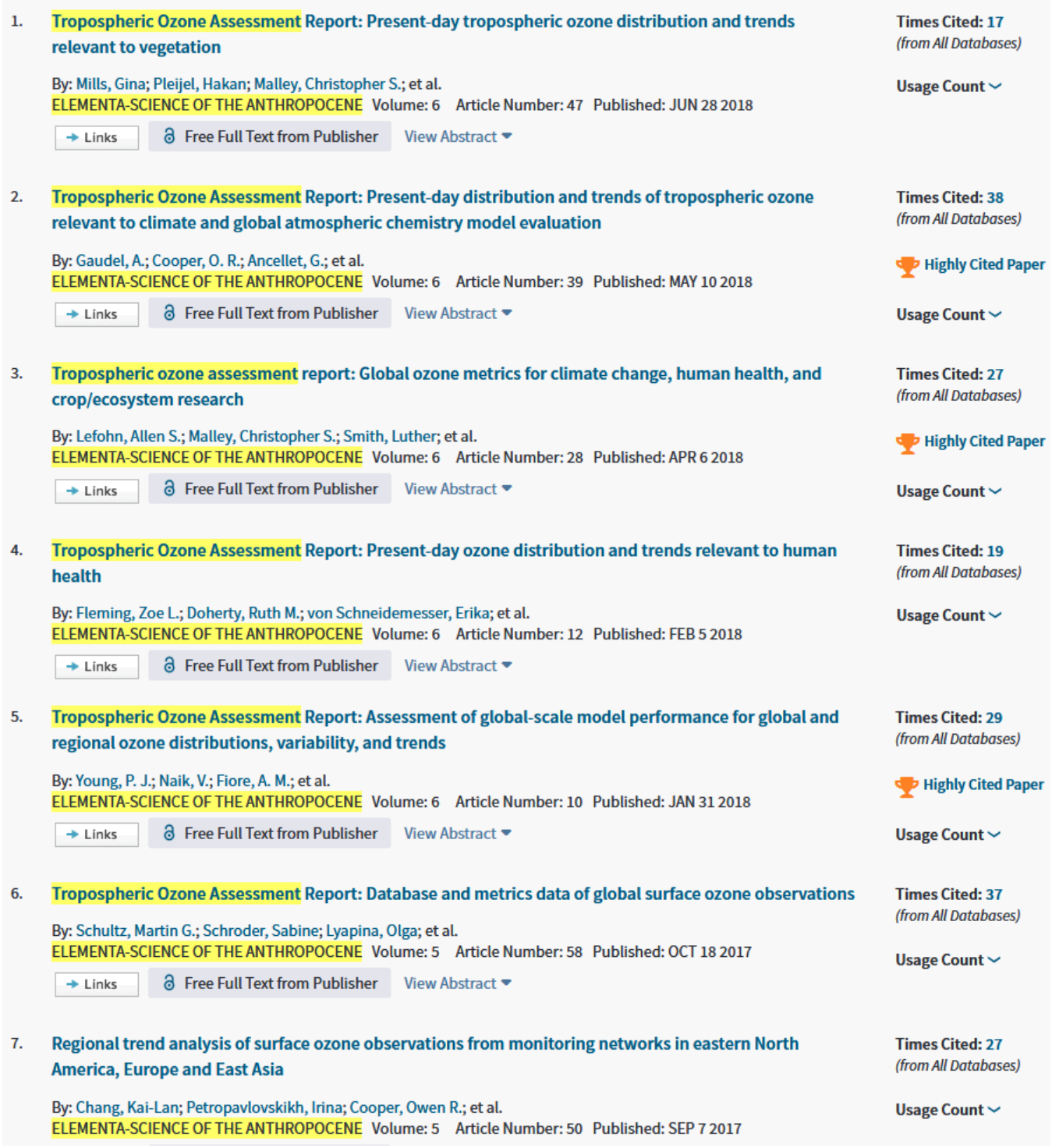

Figure 2. The number of times that TOAR papers have been cited in the peer-reviewed literature, as compiled by Web of Science; a total of 194 citations to date (updated on September 30, 2019)

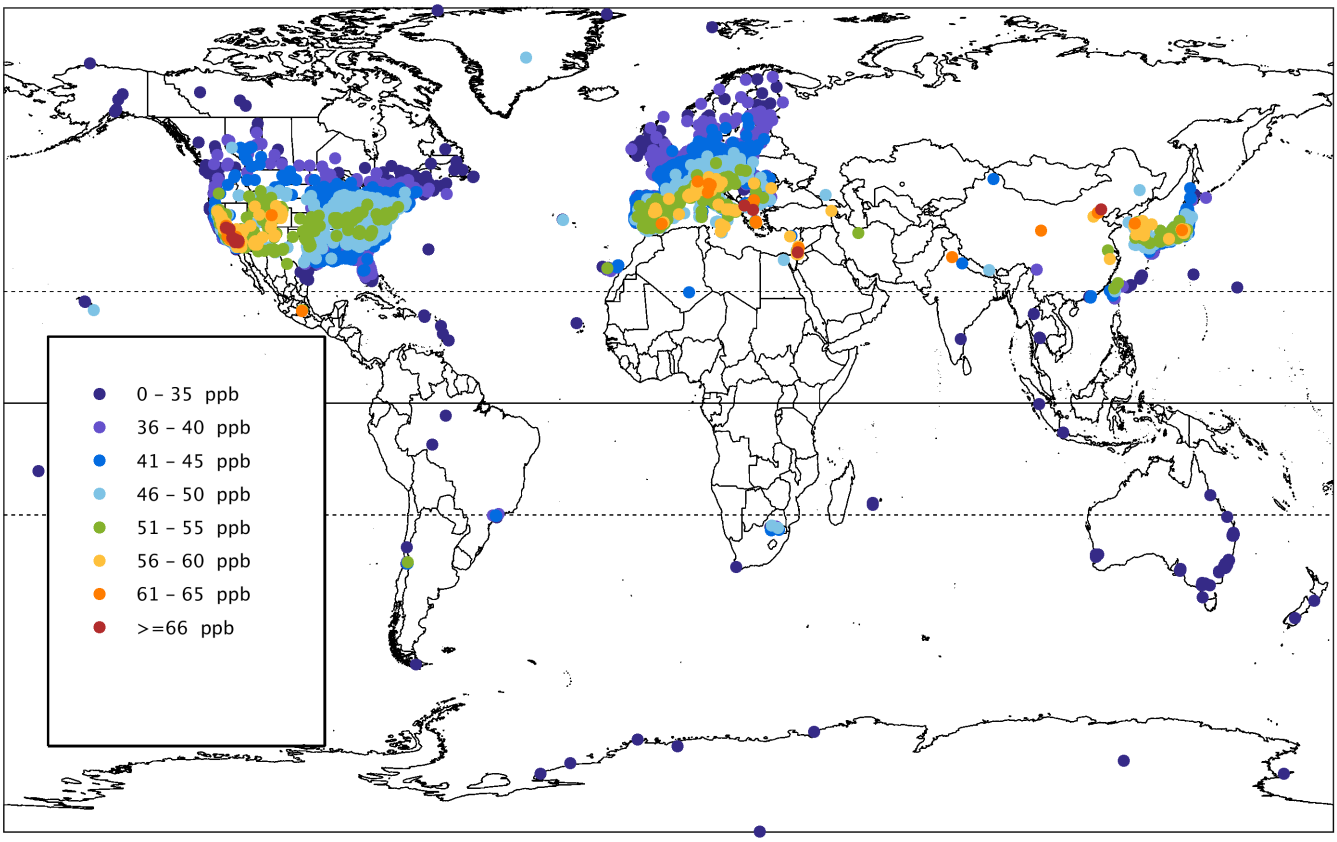

Figure 3. Present-day (2010-2014) values of the 6-month average (April-September in the N. Hemisphere, October-March in the S. Hemisphere) of maximum daily 8-hr average ozone, at all available sites (4801 total sites) in the TOAR database. Values are further averaged across the 5-yr period, 2010-2014.

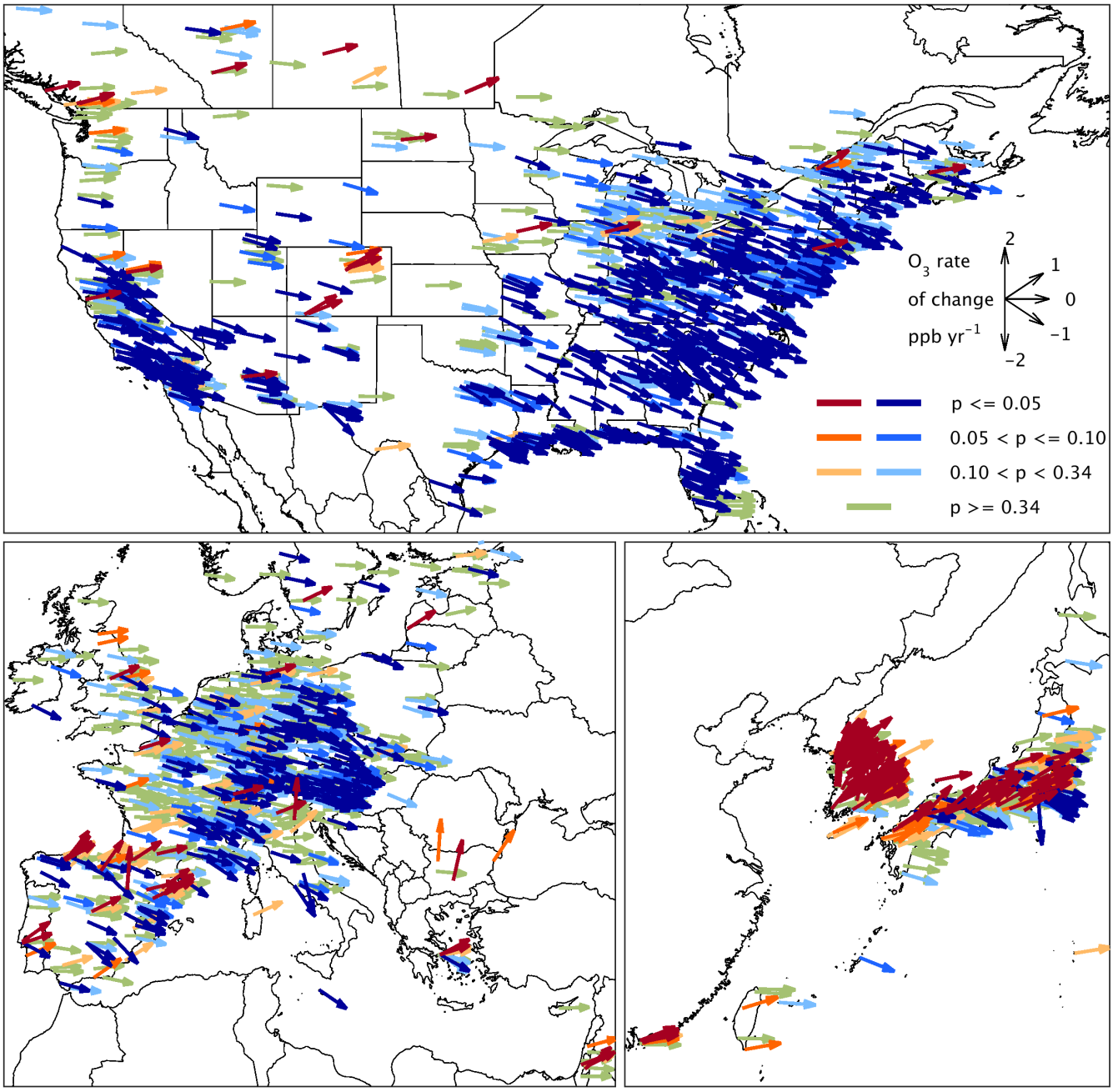

Figure 4. Trends of the 6-month average (April-September) of maximum daily 8-hr average ozone at all available sites in the TOAR database, for the period 2000-2014.