An update on ever-changing global tropospheric ozone trends

Owen R. Cooper

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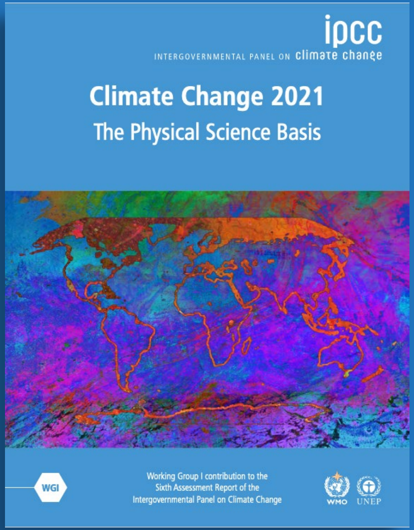
CEOS AC-VC-19 / ACSG Joint Meeting 2023
Brussels, Belgium / Hybrid
October 24 to 27, 2023

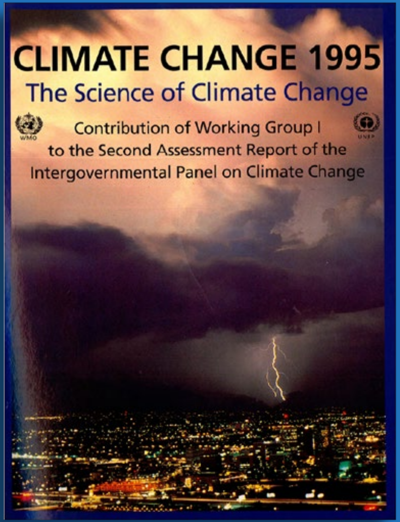
This research was supported by NOAA cooperative agreement NA22OAR4320151

Our evolving understanding of global ozone observations is documented by the assessments of the Intergovernmental Panel on Climate Change (IPCC)

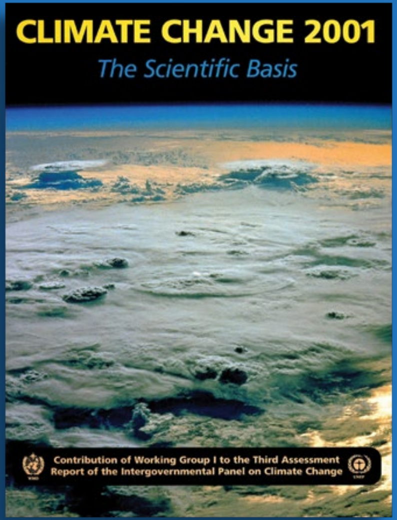


IPCC Sixth Assessment Report, 2021

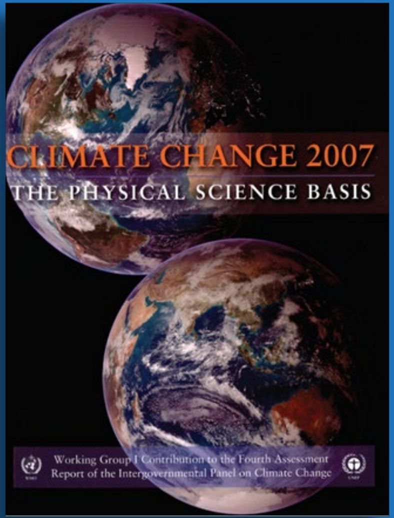
1990



1995



2001



2007

2013

IPCC's estimates of tropospheric ozone's radiative forcing (since 1750) have changed little since 1995

- 1990 no estimate
- 1995 0.4 ± 0.2 W m^{-2}
- 2001 0.35 ± 0.2 W m^{-2}
- 2007 0.35 (0.25 – 0.65) W m^{-2}
- 2013 0.40 ± 0.20 W m^{-2}
- 2021 +0.47 [0.24 to 0.70] W m^{-2} (troposphere + stratosphere)

IPCC AR6 key findings on tropospheric ozone

- Assessed the tropospheric ozone burden to be 347±28 Tg for 2010
- Ozone's effective radiative forcing (ERF) is +0.47 [0.24 to 0.70] W m^{-2} *(1750-2019, tropospheric + stratospheric ozone),* 17% of total ERF (2.72 W m^{-2} since 1750)
- The tropospheric ozone burden increased by 45% from 1850 to the present-day, and has continued to increase since the 1990s
- Ozone burden is expected to increase in the near future if emissions and methane continue to increase
- Trends at the surface do not necessarily match trends in the free troposphere

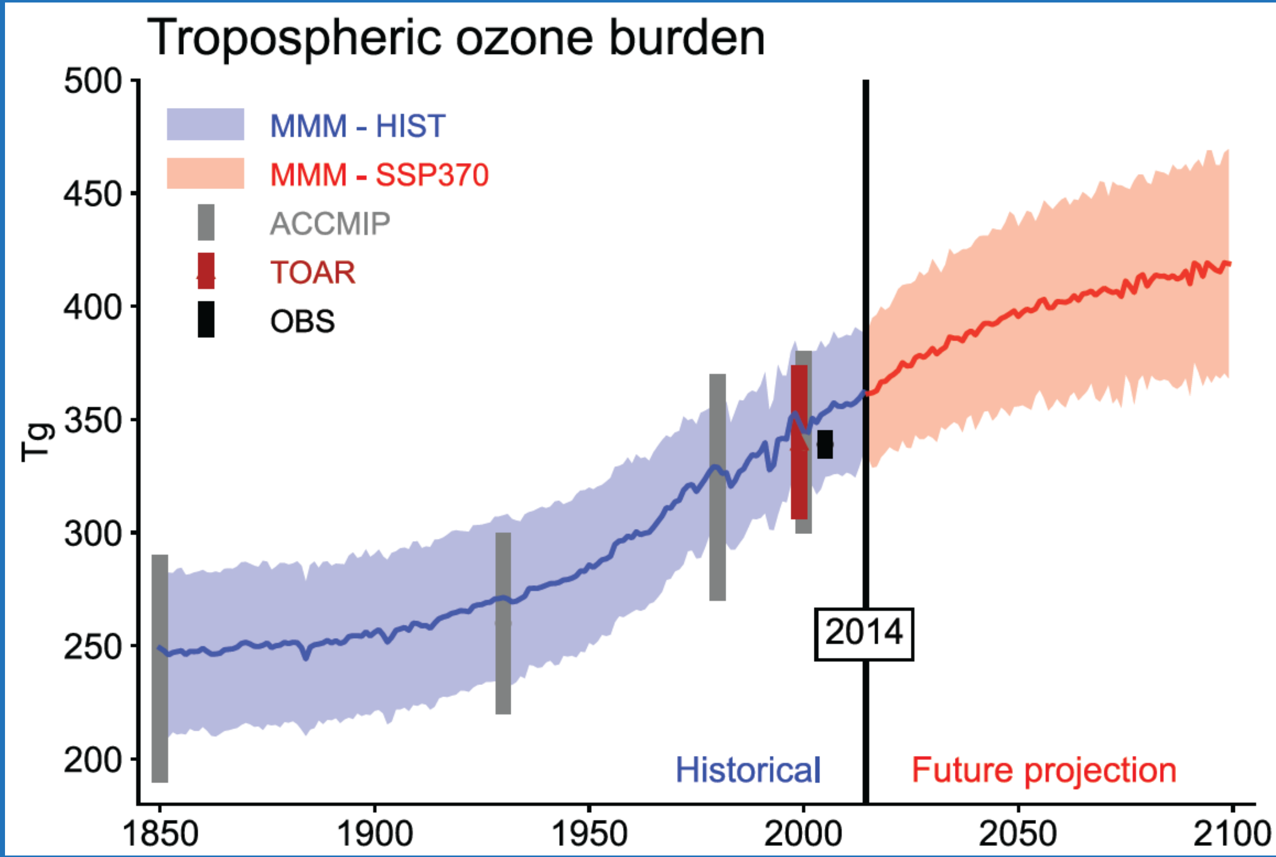


Figure 6.4 from IPCC AR6 shows the historical and future projection (SSP3-7.0) of the global tropospheric ozone burden. The observed ozone burden of 338 ± 6 Tg for 2010-2014 is from the TOST ozonesonde and IASI satellite products reported by *TOAR-Climate* [Gaudel et al. 2018].

Tropospheric ozone has increased globally since the mid-1990s, but surface trends are variable (*IPCC AR6*, 2021)

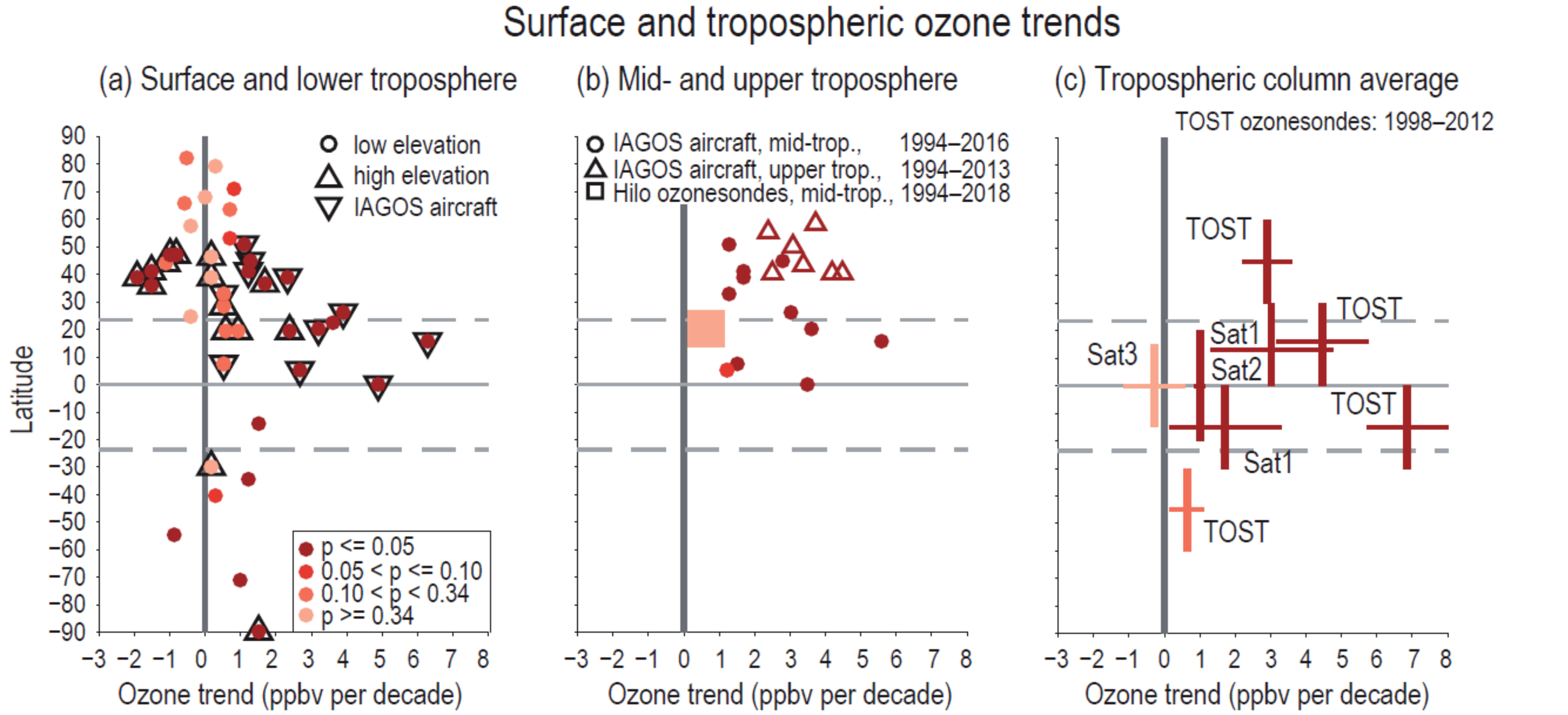
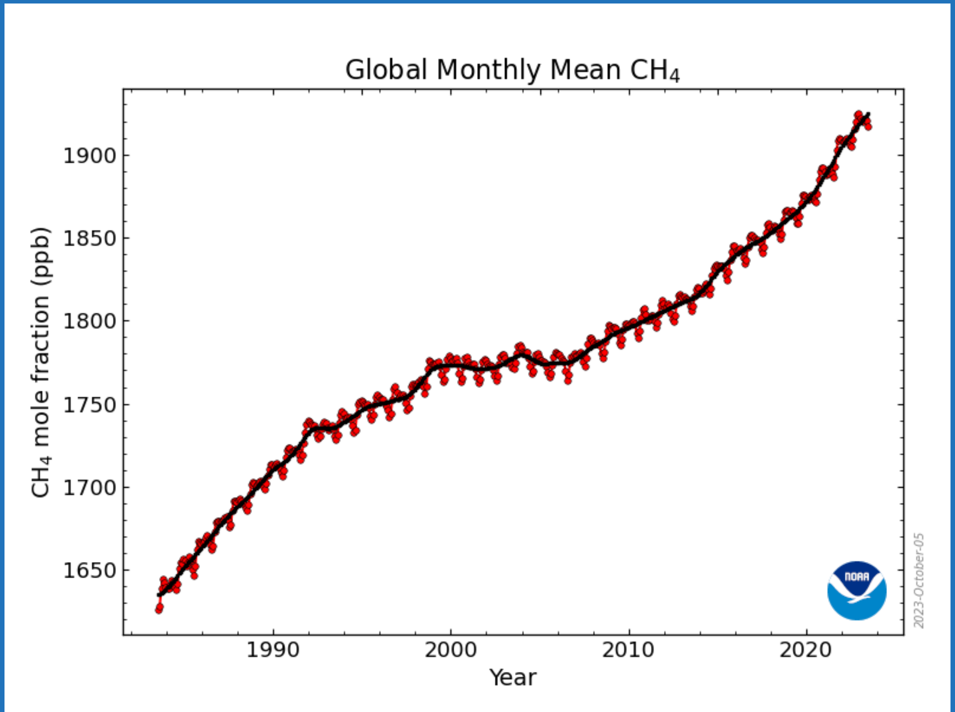
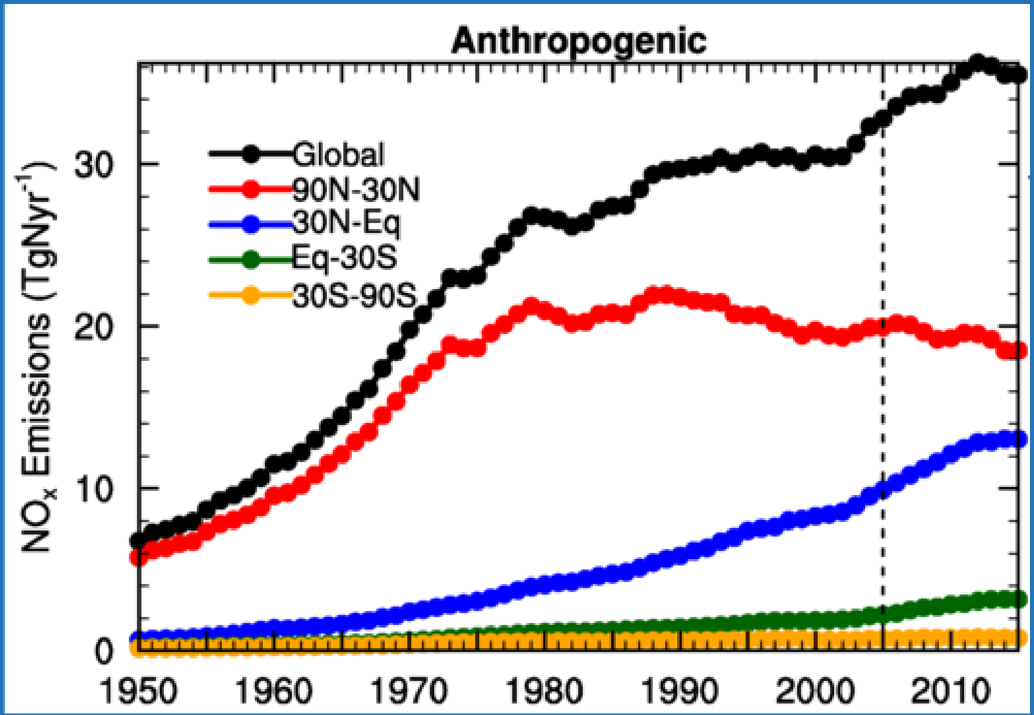


Figure 2.8, Chapter 2, IPCC AR6 WG-I, The Physical Science Basis





Methane has increased globally by 8% since 2005

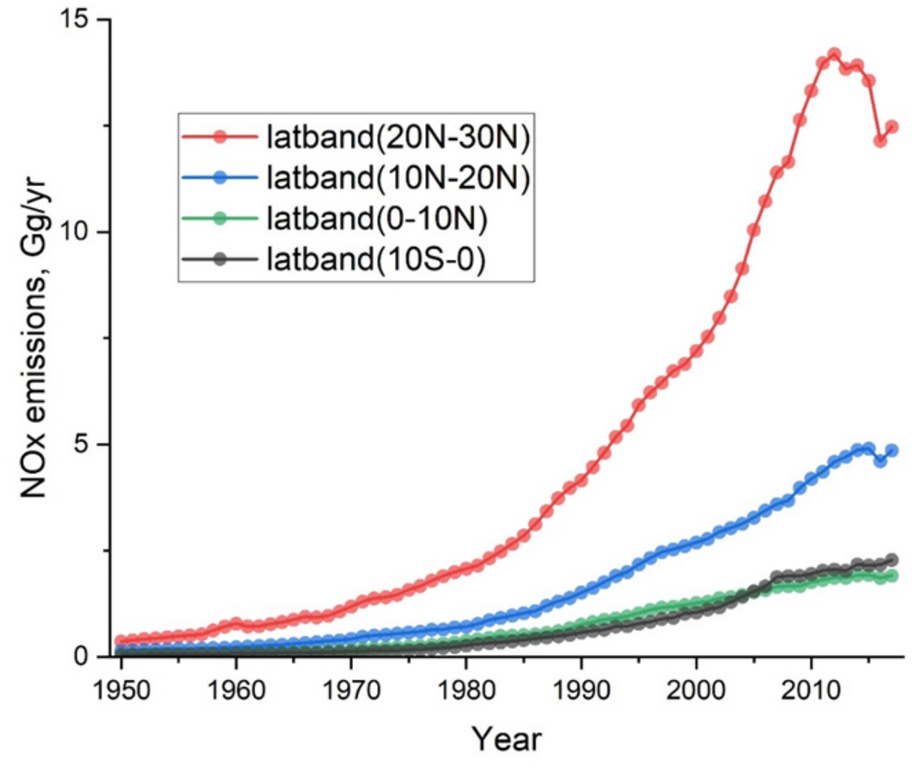
CMIP-6 global NOx emissions have levelled off since 2010

Decreases in northern mid-latitudes

Increases in the tropics

Figure produced by NOAA Global Monitoring Laboratory

Figure produced by Vaishali Naik, NOAA GFDL

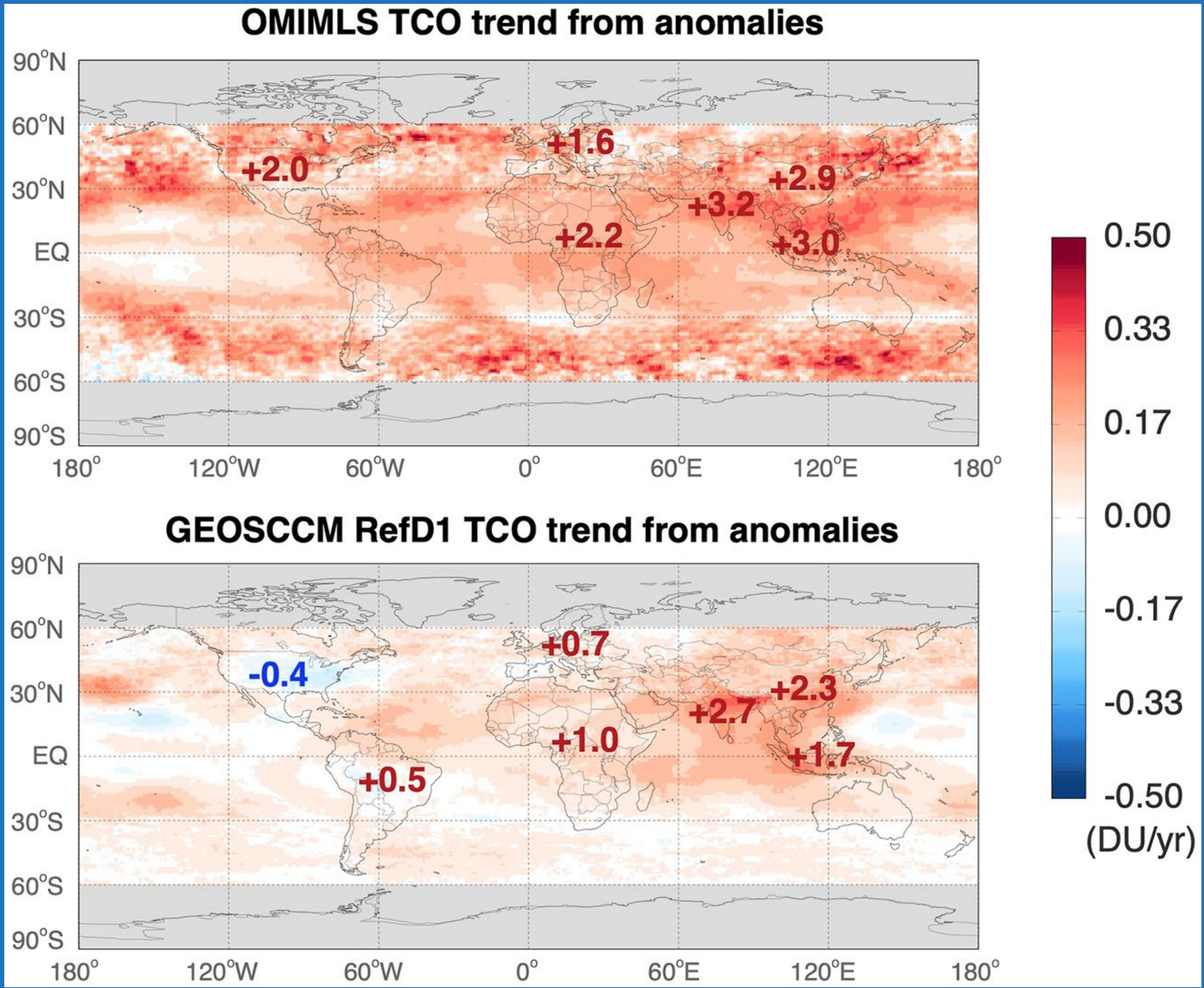


Annual anthropogenic NOx emissions across tropical South and East Asia, by latitude band (1950-2017). Figure produced by Meng Li, U. of Colorado, using the new MIXv2 emissions inventory.

Li, M., Jun-ichi Kurokawa, Qiang Zhang, Jung-Hun Woo, Tazuko Morikawa, Satoru Chatani, Zifeng Lu, Yu Song, Guannan Geng, Hanwen Hu, Jinseok Kim, O. R. Cooper, B. C. McDonald (2023), MIXv2: a long-term mosaic emission inventory for Asia (2010-2017), ACP, submitted

South and East Asia is the regional hotspot for tropospheric ozone

Observed (OMI/MLS) and modeled (GEOS-CCM) tropospheric column ozone (2005-2018)



Liu, J., Strode, S. A., Liang, Q., Oman, L. D., Colarco, P. R., Fleming, E. L., et al. (2022). Change in tropospheric ozone in the recent decades and its contribution to global total ozone. Journal of Geophysical Research: Atmospheres, 127, https://doi.org/10.1029/2022JD037170

Ozone levels in 2000-2004 (top) and 2015-2019 (bottom)

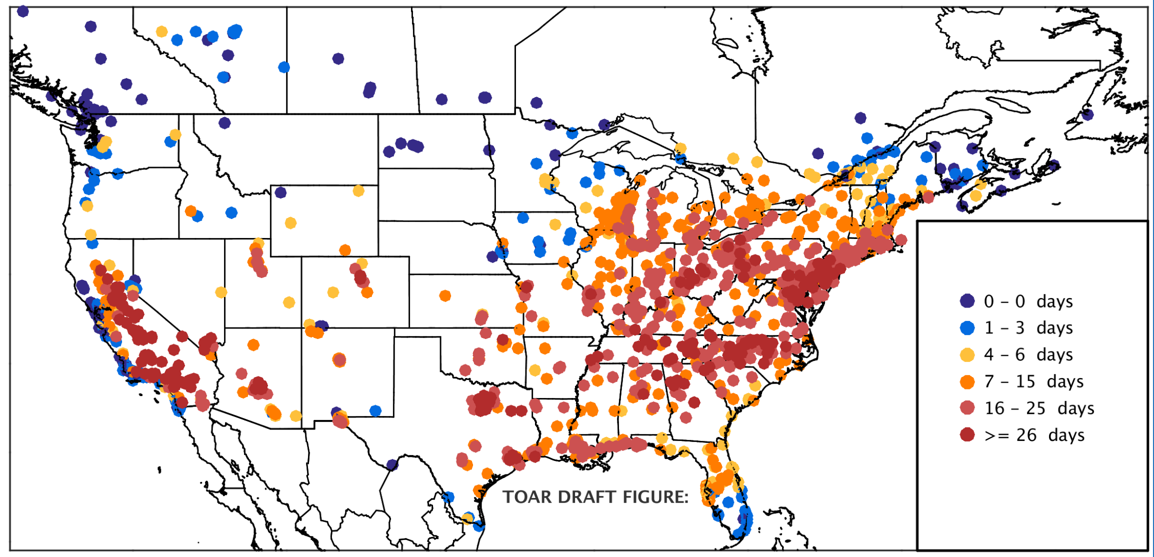
Metric: number of days per year above 70 ppb, based on MDA8 ozone

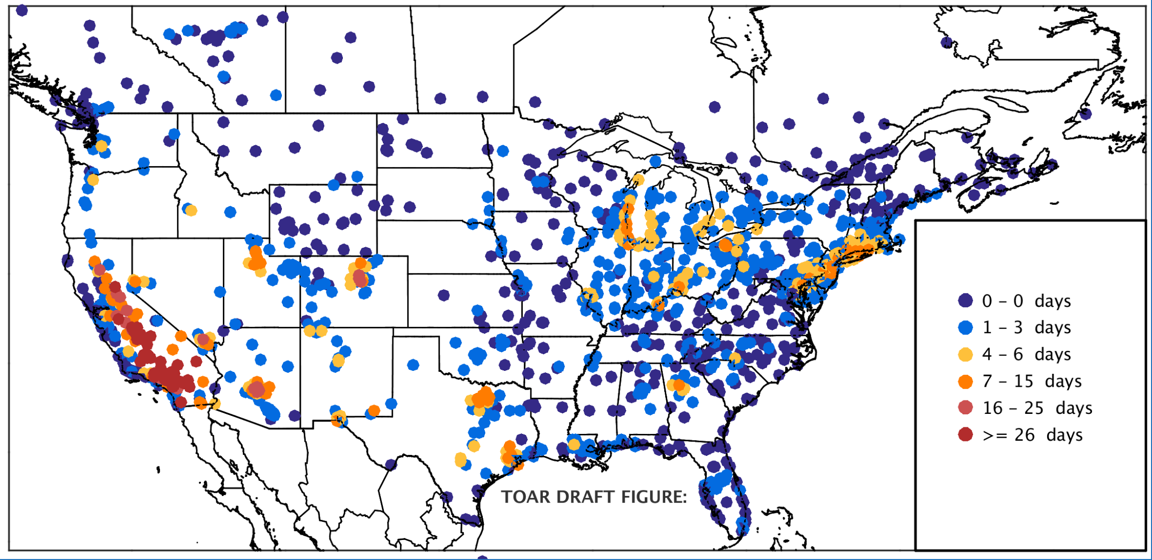
Relevance: clinical trials show respiratory impacts on healthy young adults at levels above 70 ppb; US National Ambient Air Quality Standard for ozone

Highest values (> 15 days per year):
These ozone levels have completely disappeared in the eastern USA and Ontario.
These levels persist in Denver, Phoenix. Las Vegas and much of California.

Hourly ozone values were provided by the U.S. EPA, and Canada's National Air Pollution Surveillance (NAPS) program

MDA8 and Monthly mean values were produced by the TOAR Database: https://toar-data.org/surface-data/





Remarkable ozone decreases at Big Meadows, Shenandoah National Park

The EPA CASTNET monitoring site in Shenandoah National Park is located at Big Meadows, 1073 meters above sea level on the crest of a ridgeline.

Excellent rural location for monitoring regional background ozone in the eastern USA

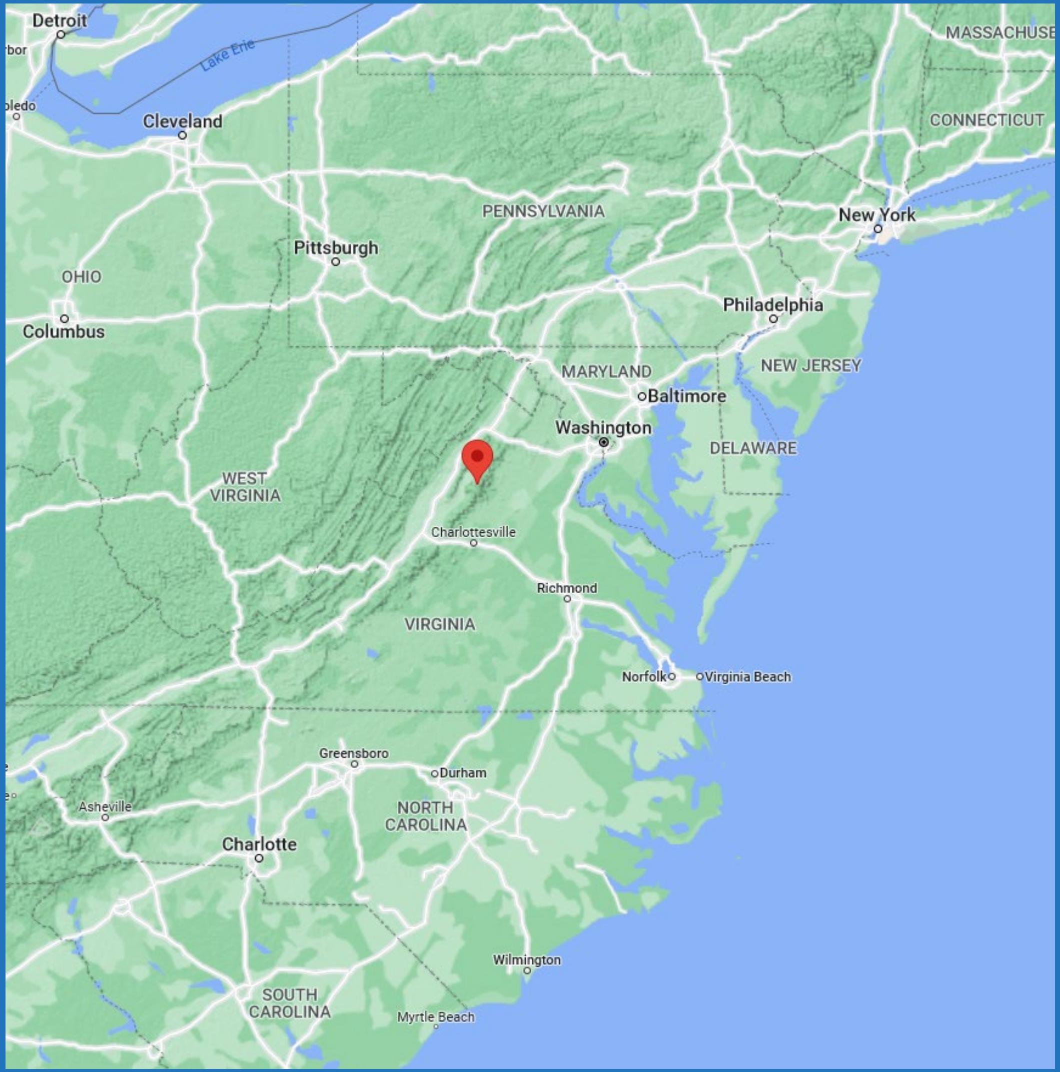
Continuous data collection began in the late 1980s

Data source:

Ozone data were collected by the EPA Clean Air Status and Trends Network (CASTNET):
https://www.epa.gov/castnet

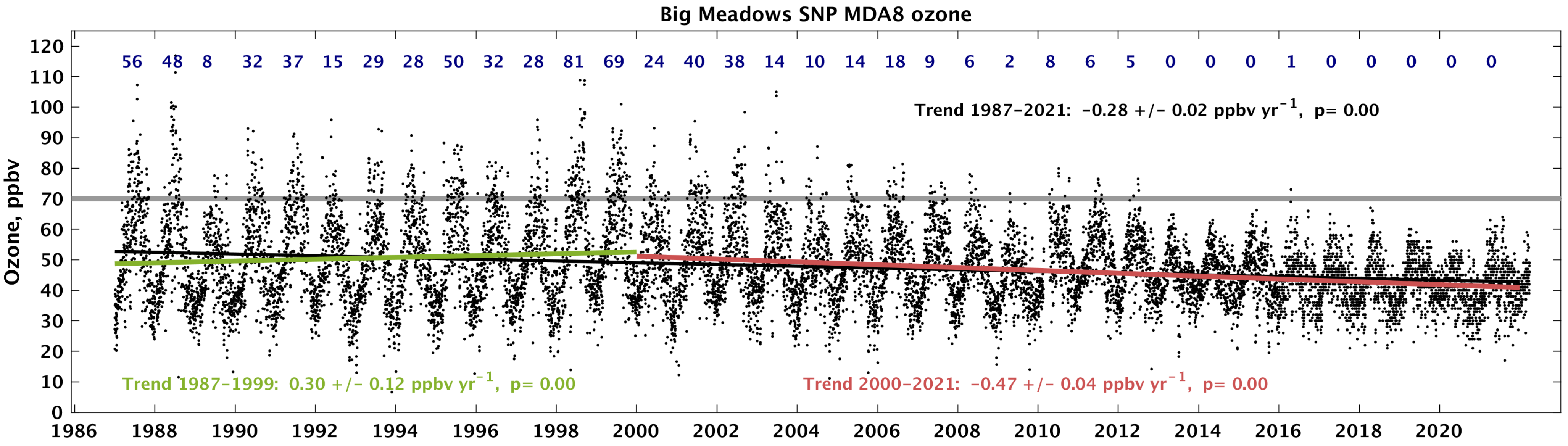
and by the National Park Service:
https://ard-request.air-resource.com/

MDA8 ozone values were provided by EPA:
https://aqs.epa.gov/aqsweb/airdata/download_files.html



Remarkable ozone decreases at Big Meadows, Shenandoah National Park

Below: every MDA8 ozone value at Big Meadows from 1987 through early 2022. Blue numbers at the top indicate the number of days per year that exceed 70 ppbv.
From 2017 to 2021 there was not a single exceedance.



Impact of the Covid-19 pandemic

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

ELSEVIER

A global observational analysis to understand changes in air quality during exceptionally low anthropogenic emission conditions

Ranjeet S. Sokhi [a,*], Vikas Singh [b], Xavier Querol [c], Sandro Finardi [d], Admir Créso Targino [e], Maria de Fatima Andrade [f], Radenko Pavlovic [g], Rebecca M. Garland [h,i,j], Jordi Massagué [c,k],
…michael [n],
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…amacho [p],
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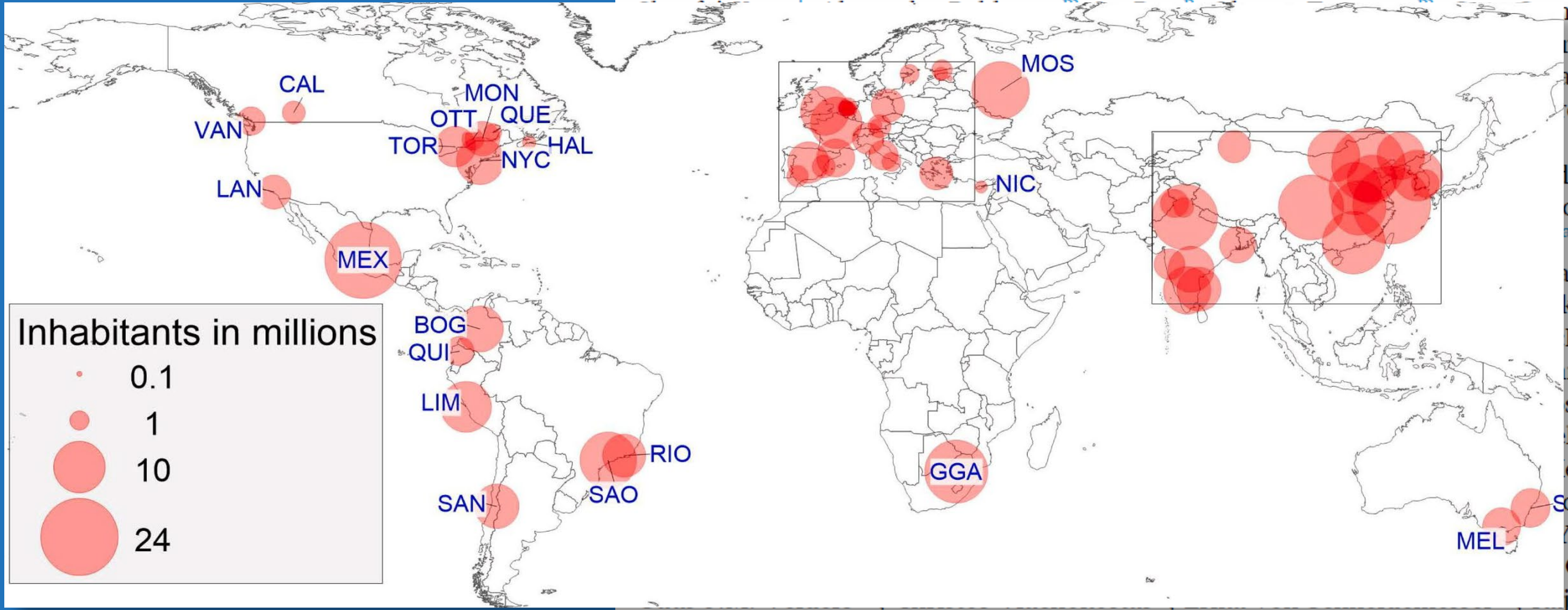
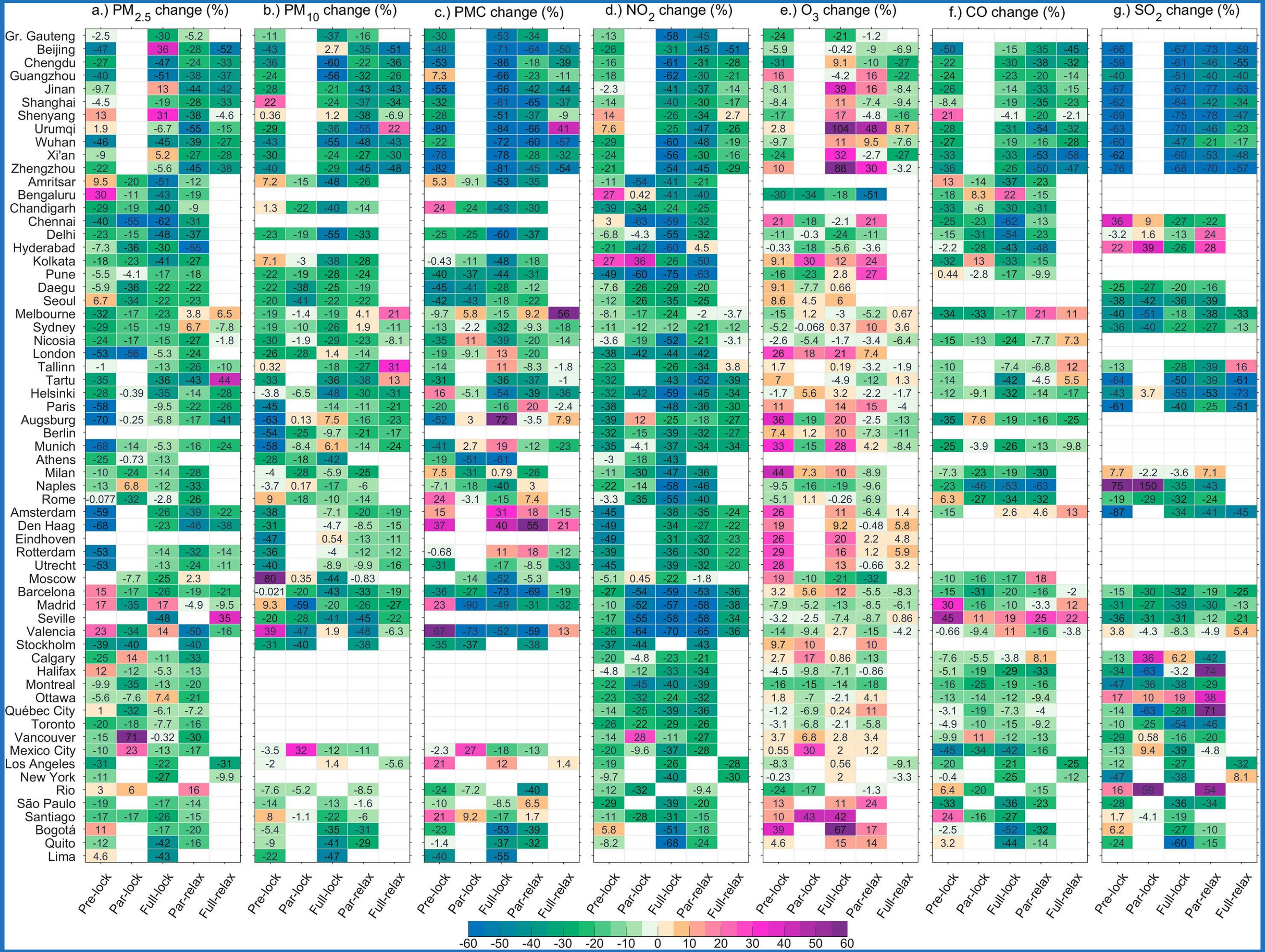
…George Tsegas [y],
…jasree VPM [a],
Ravi Yadav [q], Rasa Zalakeviciute [bj], Miguel Zavala [ag]



Impact of the Covid-19 pandemic

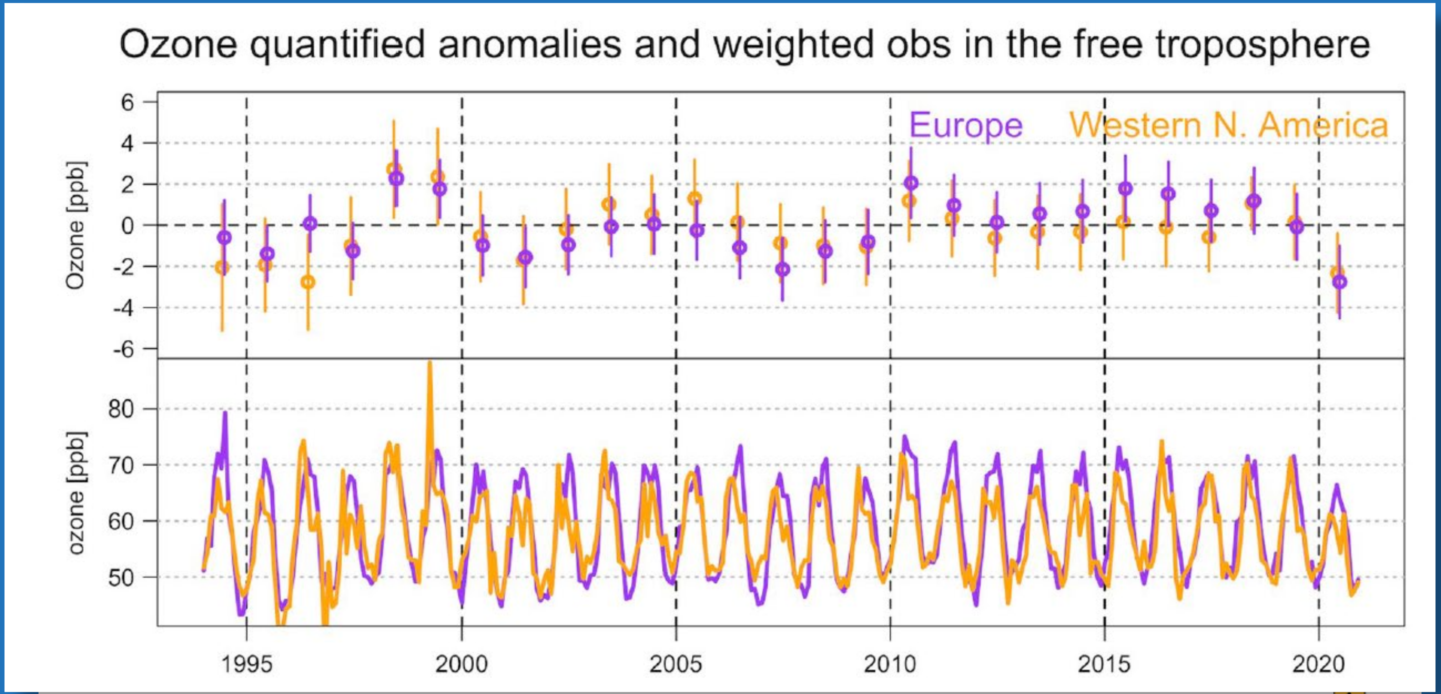
At the surface, ozone generally increased in urban areas.

-due to the reduction in NO_x emissions in springtime months, when NO_x often destroys ozone in urban settings



Impact of the Covid-19 pandemic

In the free troposphere, clear ozone decreases (~5%) were observed at northern mid-latitudes



RESEARCH ARTICLE

10.1029/2021AV000542

Special Section:
The COVID-19 pandemic: linking health, society and environment

Impact of the COVID-19 Economic Downturn on Tropospheric Ozone Trends: An Uncertainty Weighted Data Synthesis for Quantifying Regional Anomalies Above Western North America and Europe

Kai-Lan Chang[1,2], Owen R. Cooper[1,2], Audrey Gaudel[1,2], Marc Allaart[3], Gerard Ancellet[4], Hannah Clark[5], Sophie Godin-Beekmann[4], Thierry Leblanc[6], Roeland Van Malderen[7], Philippe Nédélec[8], Irina Petropavlovskikh[1,9], Wolfgang Steinbrecht[10], René Stübi[11], David W. Tarasick[12], and Carlos Torres[13]

Key Points:

- 2020 is the only year that both Europe and western North America show strong negative tropospheric ozone

Impact of the Covid-19 pandemic

Satellite instruments also detected ozone decreases at northern mid-latitudes.

Geophysical Research Letters

RESEARCH LETTER

10.1029/2022GL098712

Key Points:

- NASA satellite data show that spring-summer decreases in tropospheric ozone reported throughout the Northern Hemisphere (NH) in 2020 have repeated again in 2021

NASA Satellite Measurements Show Global-Scale Reductions in Free Tropospheric Ozone in 2020 and Again in 2021 During COVID-19

Jerry R. Ziemke[1,2], Natalya A. Kramarova[1], Stacey M. Frith[1,3], Liang-Kang Huang[1,3], David P. Haffner[1,3], Krzysztof Wargan[1,3], Lok N. Lamsal[1,4], Gordon J. Labow[1,3], Richard D. McPeters[1], and Pawan K. Bhartia[1,5]

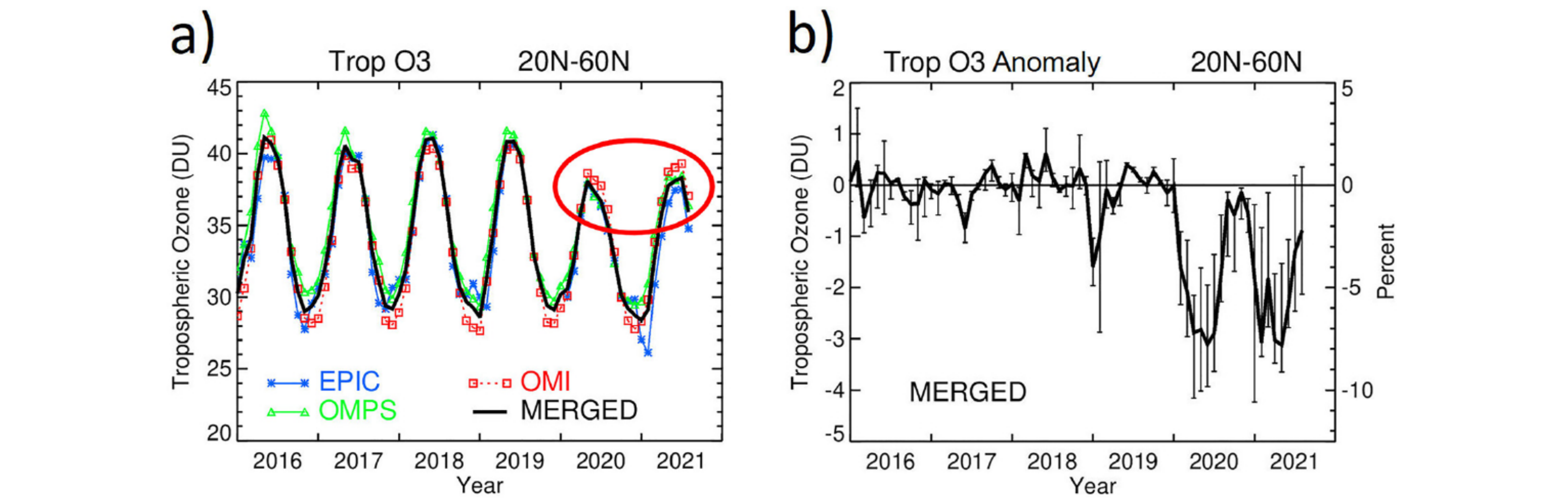


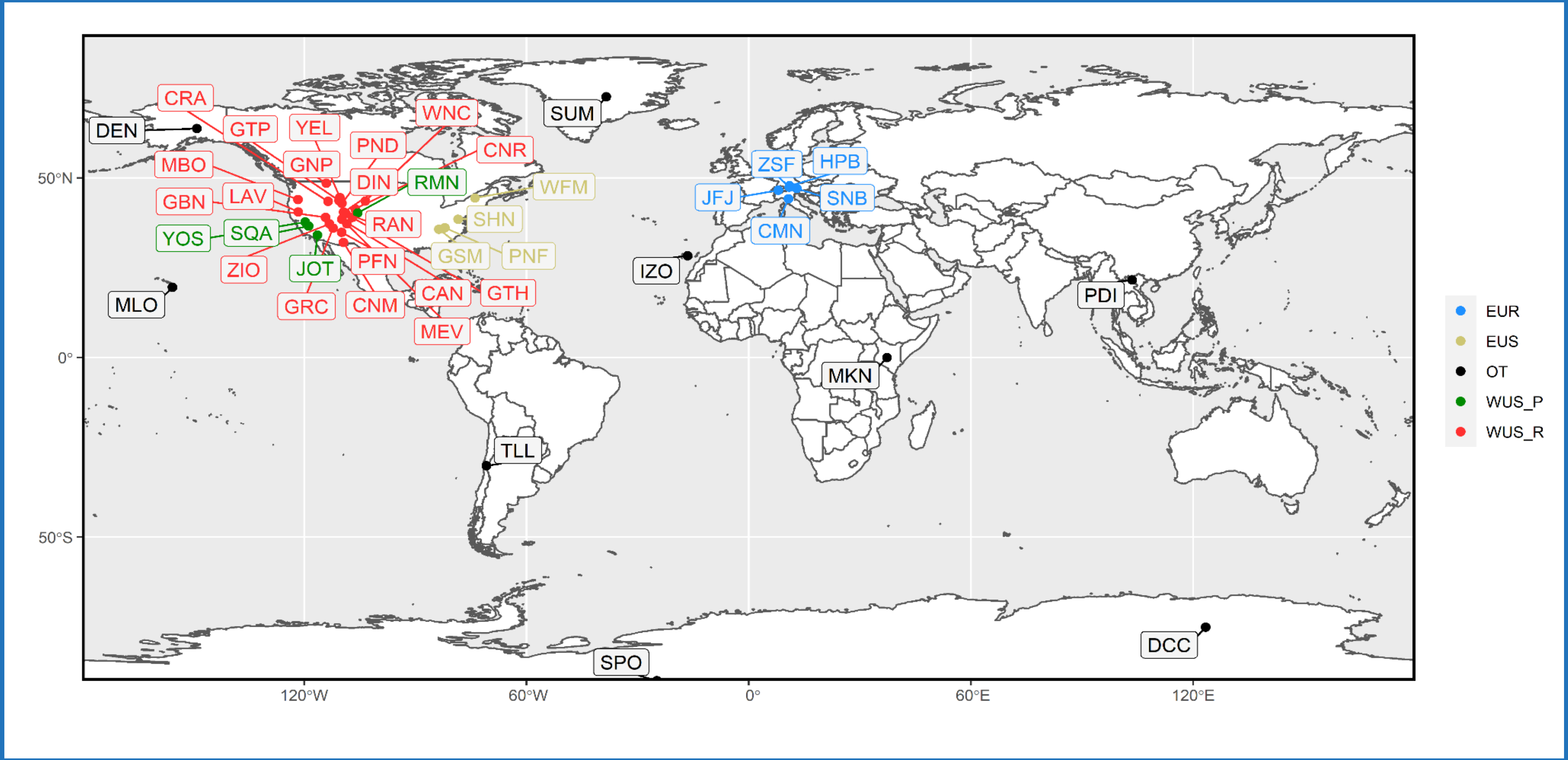
Figure 1. (a) Monthly time series of tropospheric column ozone (TCO) (in DU) averaged over the NH for 20°N–60°N for the three instrument measurements along with the combined EPIC + OMPS + OMI merged time series (indicated). Red oval highlights anomalous drops of ~3 DU in spring-summer of both 2020 and 2021. (b) Inter-annual anomaly time series of merged monthly TCO (in DU) for 2016–2021 relative to the baseline TCO (see text). Vertical bars show absolute maximum and absolute minimum TCO inter-annual anomalies for the three instruments during each month about the merged mean value.

https://doi.org/10.5194/egusphere-2023-1737
Preprint. Discussion started: 16 August 2023

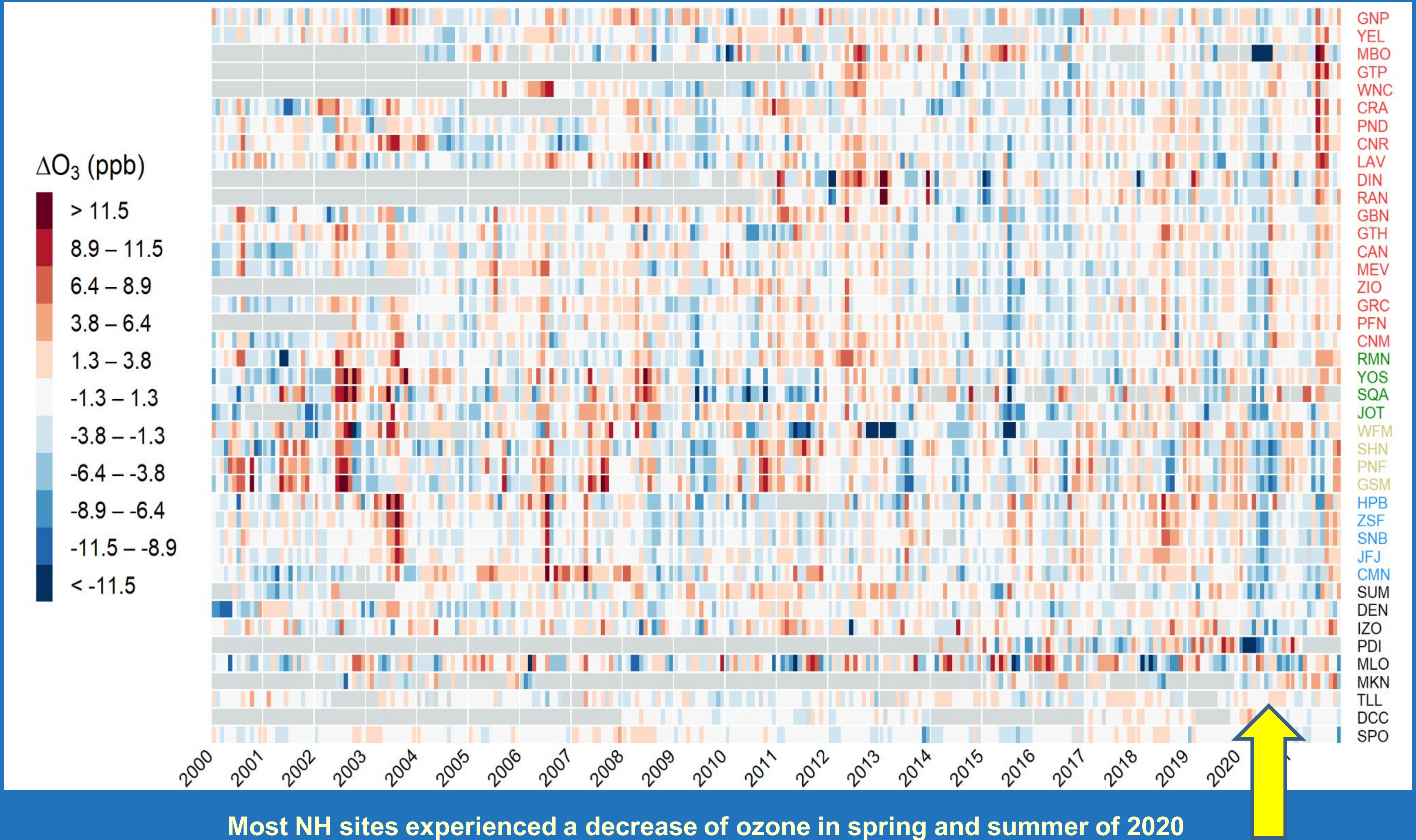
Fingerprints of the COVID-19 economic downturn and recovery on ozone anomalies at high-elevation sites in North America and Western Europe

Davide Putero[1], Paolo Cristofanelli[2], Kai-Lan Chang[3], Gaëlle Dufour[4], Gregory Beachley[5], Cédric Couret[6], Peter Effertz[7], Daniel A. Jaffe[8], Dagmar Kubistin[9], Jason Lynch[5], Irina Petropavlovskikh[7], Melissa Puchalski[5], Timothy Sharac[5], Barkley C. Sive[10], Martin Steinbacher[11], Carlos Torres[12], and Owen R. Cooper[3]

Manuscript under review with ACP; submitted to the TOAR-II Community Special Issue



Monthly ozone anomalies were calculated for 41 high elevation sites (all rural or remote)



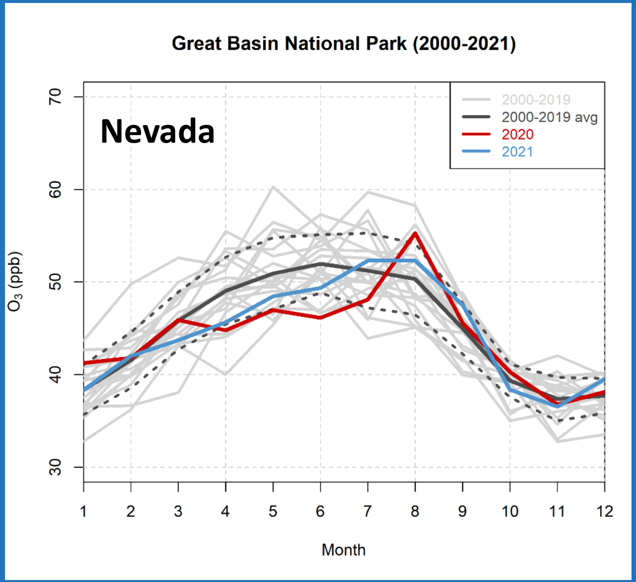
Most NH sites experienced a decrease of ozone in spring and summer of 2020

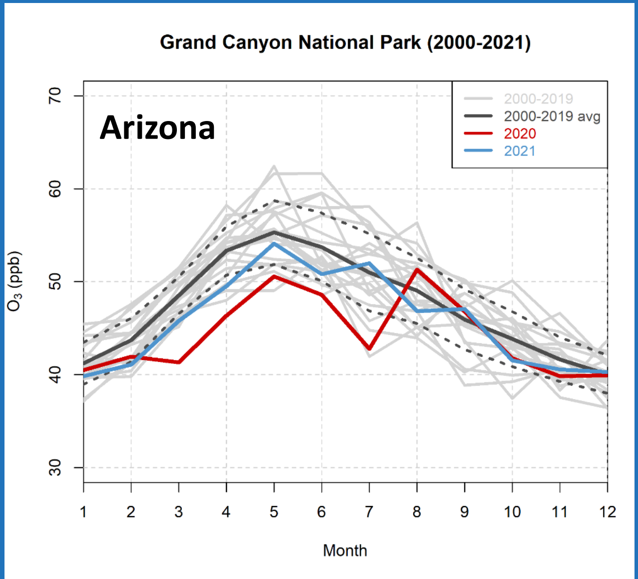
Strongest decreases were in the western USA in spring 2020 (-9%) and the eastern USA in summer 2020 (-12%)

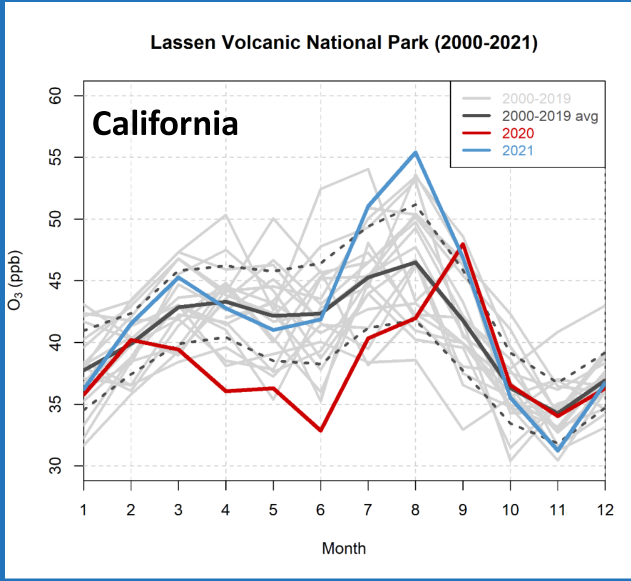
Table 2: Seasonal average anomalies for the different regions considered in this study. Values in brackets indicate percentage variations. The region abbreviations are as follows: WUS_R = Western US "rural", WUS_P = Western US "polluted", EUS = Eastern US, EUR = Europe, OT = Other.

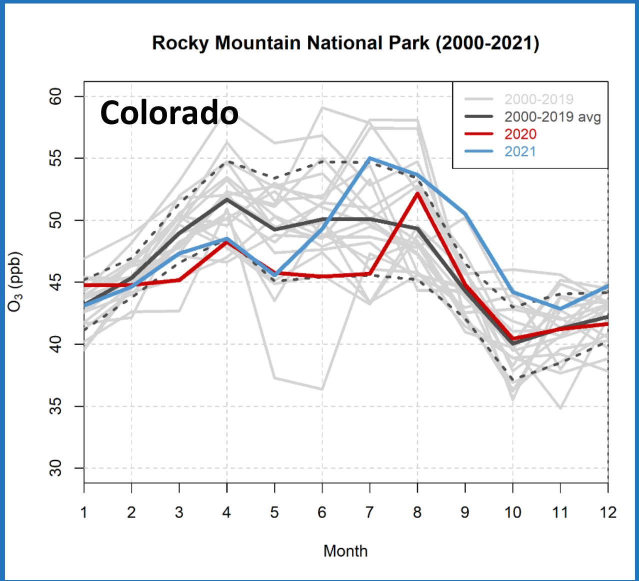
Season	WUS_R	WUS_P	EUS	EUR	OT
MAM 2020	-3.0 ppb (-6%)	-4.1 ppb (-9%)	-2.4 ppb (-4%)	-2.0 ppb (-3%)	-2.1 ppb (-3%)
JJA 2020	-2.2 ppb (-5%)	-2.7 ppb (-4%)	-5.5 ppb (-12%)	-4.7 ppb (-8%)	-1.5 ppb (-5%)
MAM 2021	-0.9 ppb (-2%)	0.7 ppb (3%)	1.0 ppb (3%)	-2.6 ppb (-4%)	-1.4 ppb (-1%)
JJA 2021	2.8 ppb (6%)	1.4 ppb (3%)	-3.7 ppb (-8%)	-2.5 ppb (-4%)	0.3 ppb (1%)

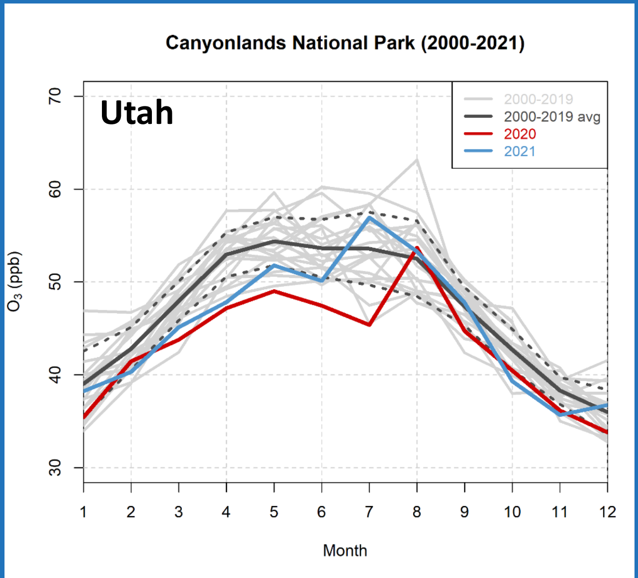
Sites in the western USA show positive ozone anomalies in August-September 2020 and July-August 2021, due to impacts from wildfire smoke.



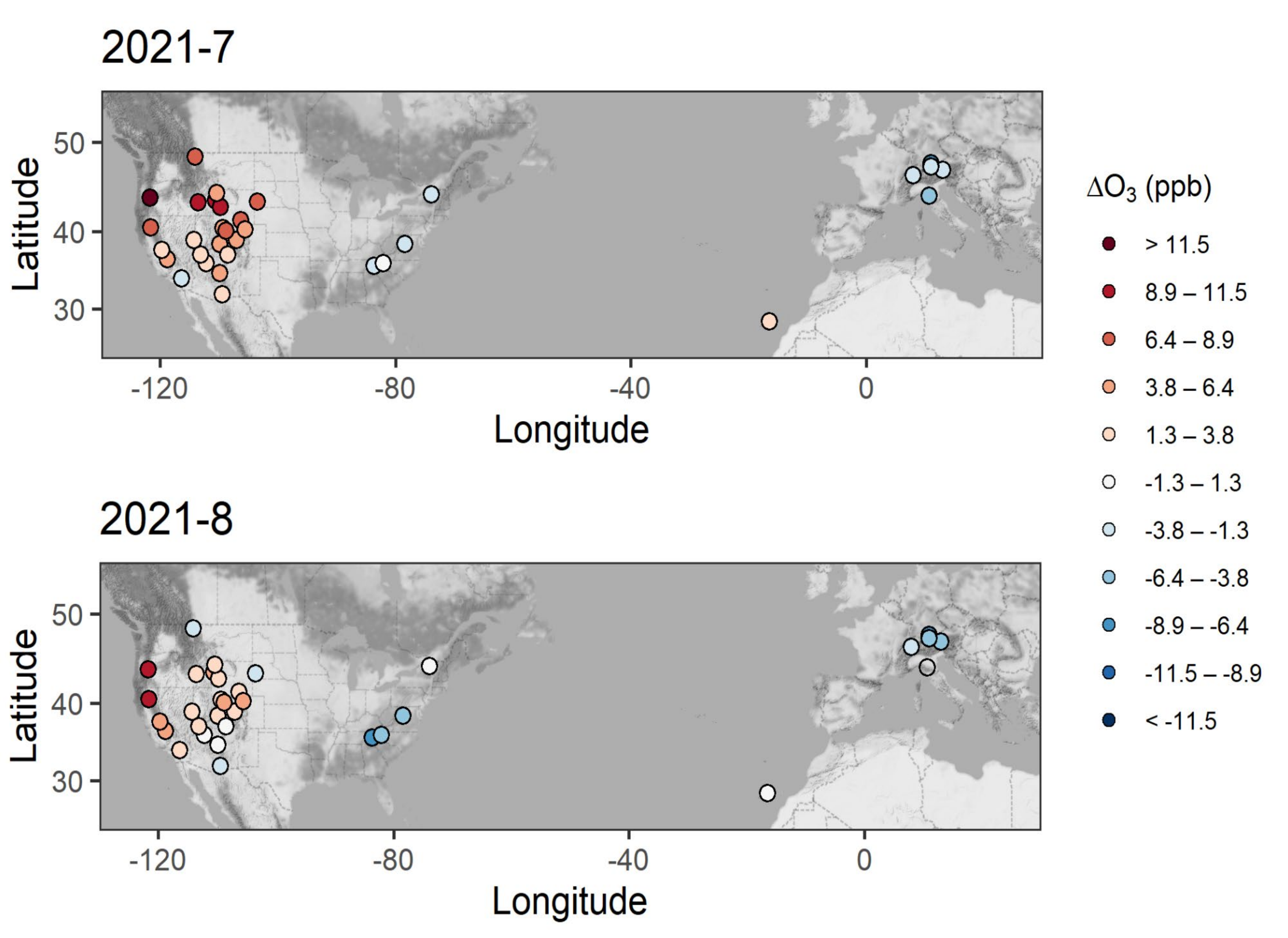








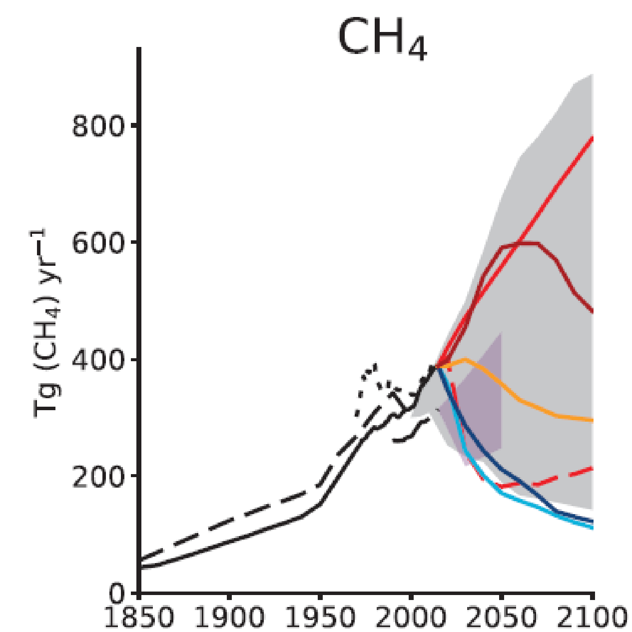
Strong positive anomalies across the western USA in summer 2021 were associated with large wildfires.

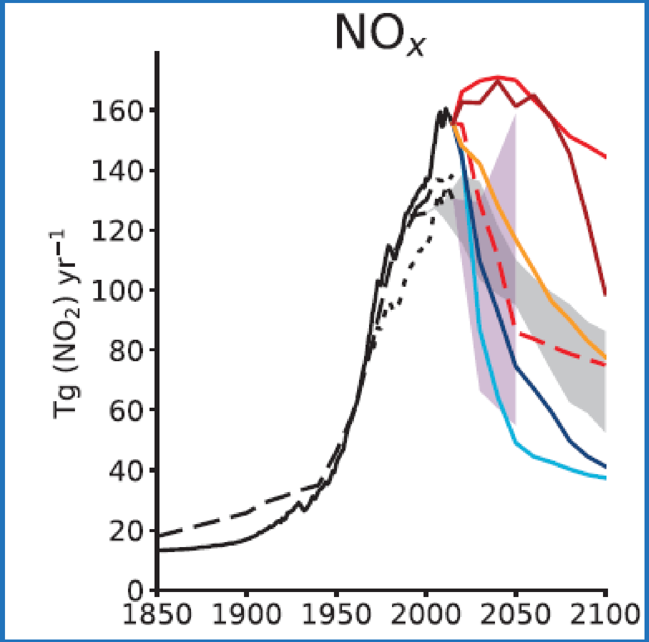


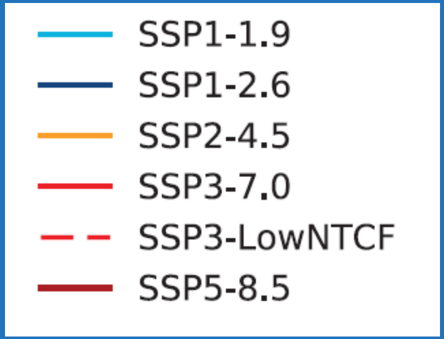
Possible ozone pathway in the 21st Century

A potential Shared Socio-economic Pathway for the 21st Century is SSP3-7.0

- Focus is on economic development and security
- A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions
- Methane emissions increase throughout the 21st Century
- NOx emission peak by mid-century and then decline







From:
Figure 6.18, Chapter 6, IPCC AR6 WG-I, The Physical Science Basis

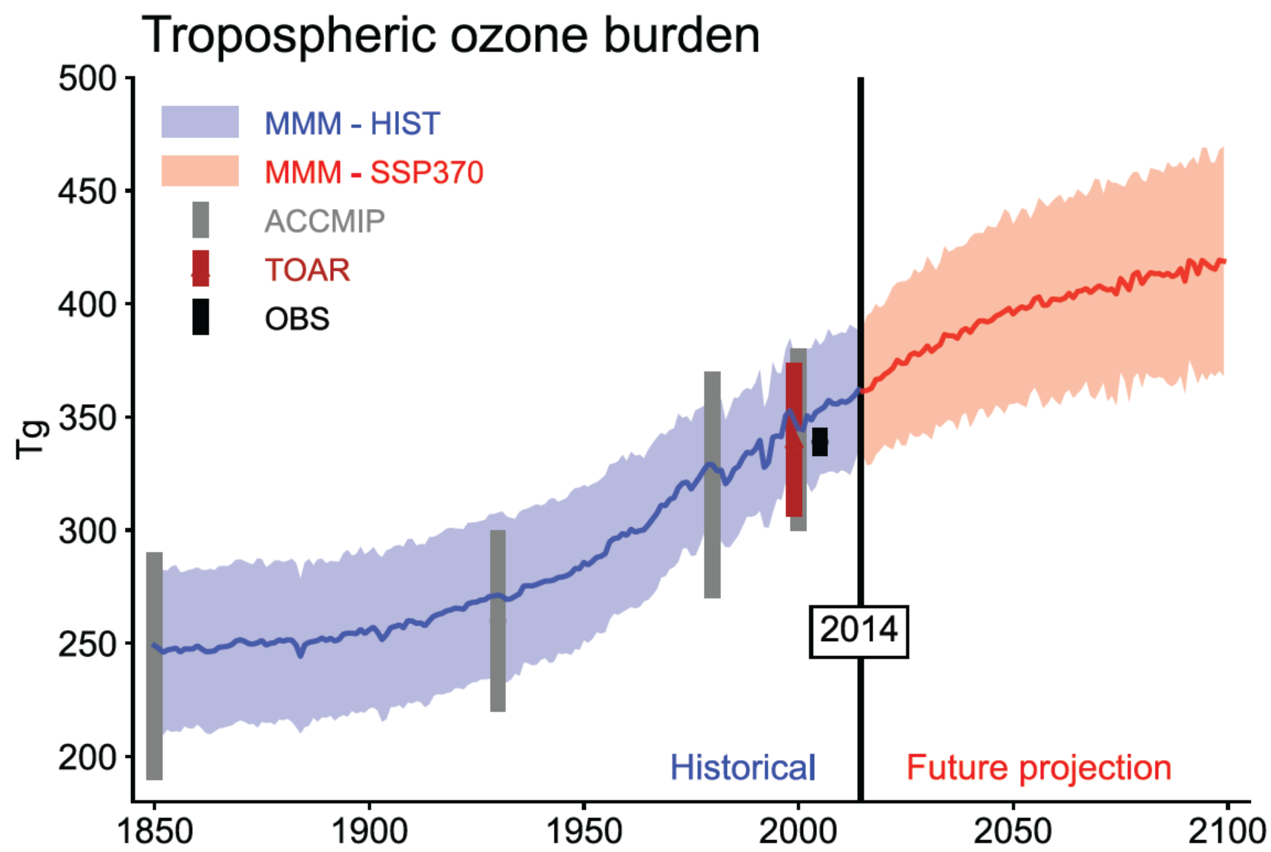


Figure 6.4 from IPCC AR6 shows the historical and future projection (SSP3-7.0) of the global tropospheric ozone burden. The observed ozone burden of 338 ± 6 Tg for 2010-2014 is from the TOST ozonesonde and IASI satellite products reported by *TOAR-Climate* [Gaudel et al. 2018].

Many regions of the world are experiencing an increase in heatwaves.

The number of days per year with daily maximum temperature >35⁰ C is expected to increase throughout the 21st century.

UNEP (2022) predicts an increase of 50% in the number of wildfires by 2100.

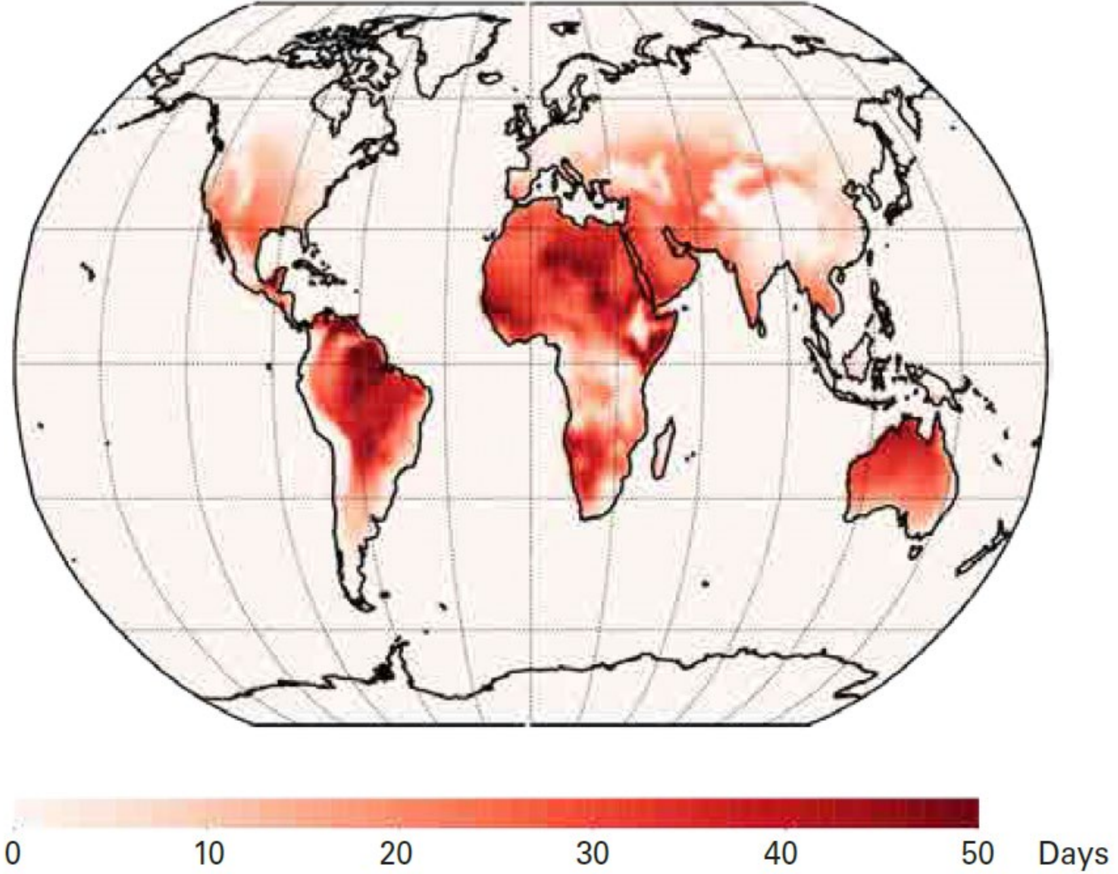


Figure 1. Change in the number of days per year with daily maximum surface temperatures above 35 °C, relative to an 1850–1900 baseline, as predicted by 27 numerical models, in a world that will have experienced 1.5 °C warming (based on the Shared Socioeconomic Pathway SSP5-8.5), globally averaged

Source: Figure produced using data from the IPCC Working Group I Interactive Atlas: https://interactive-atlas.ipcc.ch/

UNEP, Spreading Like Wildfire: The Rising Threat of Extraordinary Landscape Fires. UNEP: Nairobi, 2022.

WMO Air Quality and Climate Bulletin, No. 3, September 6, 2023; a publication of the World Meteorological Organization, https://library.wmo.int/idurl/4/62090

Possible ozone pathway in the 21st Century

A potential Shared Socio-economic Pathway for the 21st Century is SSP3-7.0

- The "climate penalty" will exacerbate ozone increases in some regions, by ~20%
- Will be strongest in regions with highest emissions: South and East Asia
- The penalty will impact ¼ of the global population

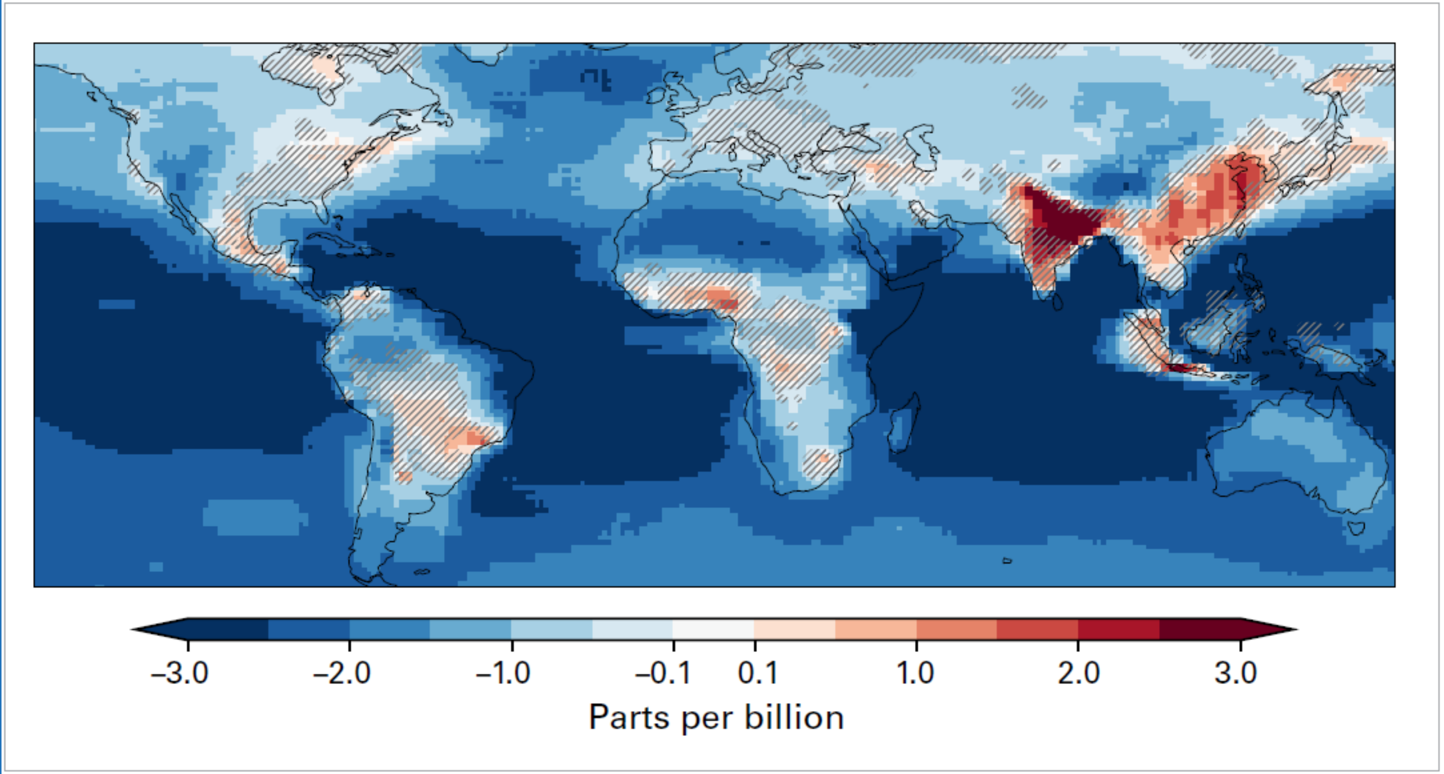


Figure 3. Projected changes in surface ozone levels due to climate change alone in the late part of the twenty-first century (2055–2081), if average global surface temperature rises by 3.0 °C above the average temperature of the late nineteenth century (1850–1900). This projection assumes increasing air pollutant emissions in developing regions and is based on simulations from five global chemistry-climate models. Hatching indicates regions where less than four out of five models agree on the projected changes, therefore greater confidence is placed on the regions without hatching. See Zanis et al. (2022) for further details.

Future Outlook:

A business as usual scenario (e.g. SSP3-7.0) will increase the tropospheric ozone burden.

An increase in heatwaves will produce an ozone climate penalty in high emissions regions, such as South and East Asia.

Wildfires will increase globally, providing an extra source of ozone precursors.

nature geoscience
LETTERS
PUBLISHED ONLINE: 7 NOVEMBER 2016 | DOI: 10.1038/NGEO2827

Tropospheric ozone change from 1980 to 2010 dominated by equatorward redistribution of emissions

Yuqiang Zhang[1†], Owen R. Cooper[2,3], Audrey Gaude
Shin-Ya Ogino[6] and J. Jason West[1*]

The global tropospheric ozone burden increased by 9% from 1980 to 2010.

Half of the increase was due to the increase of emissions.

The other half was caused by the equatorward shift of emissions.

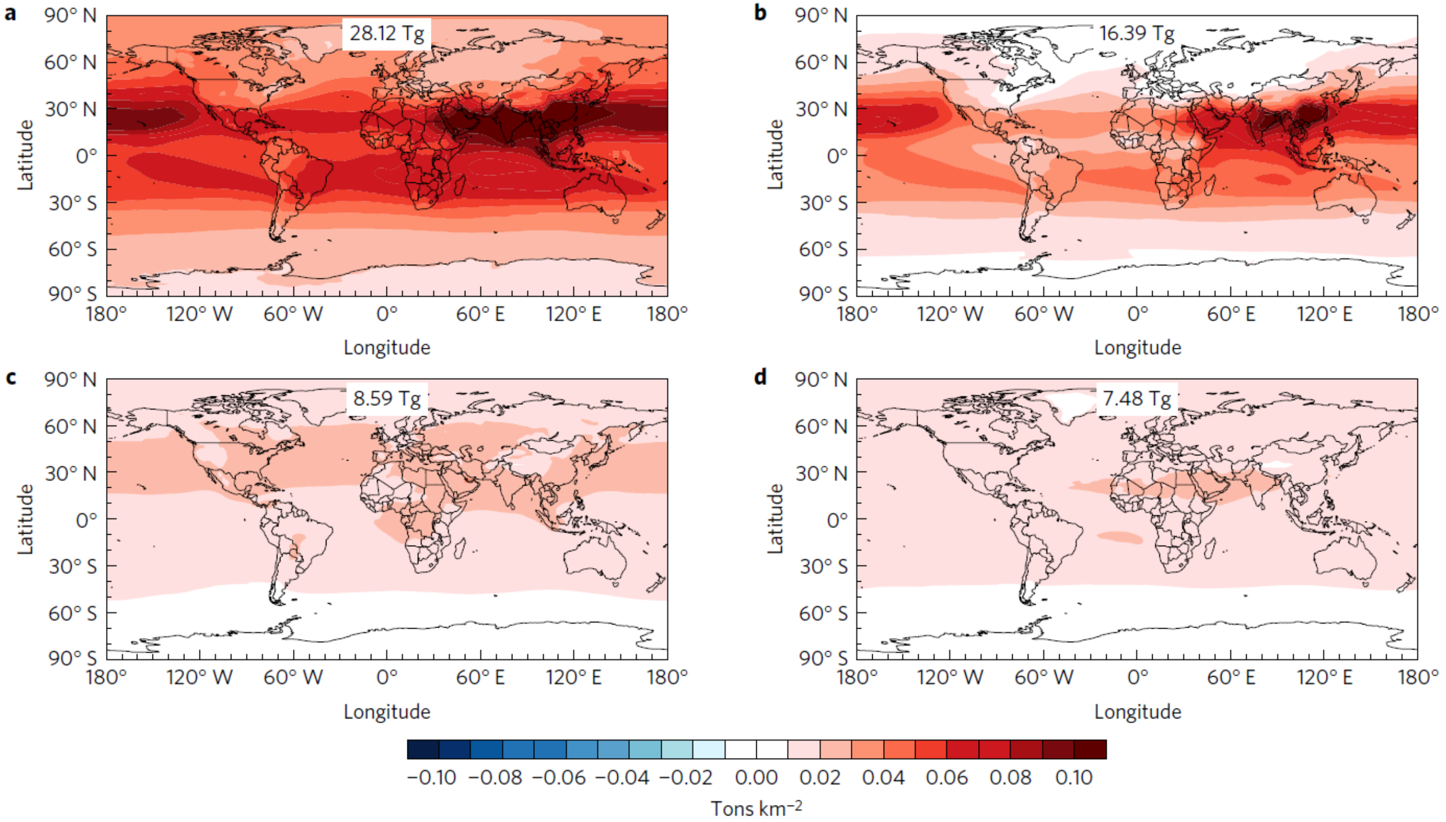


Figure 2 | Spatial distributions for ΔB_{O_3} (tons km^{-2}) from 1980 to 2010. a, Total changes from 1980 to 2010. **b–d**, Influences of changes in the global emissions spatial distribution (**b**), the global emissions magnitude (**c**), and global CH_4 mixing ratio (**d**).

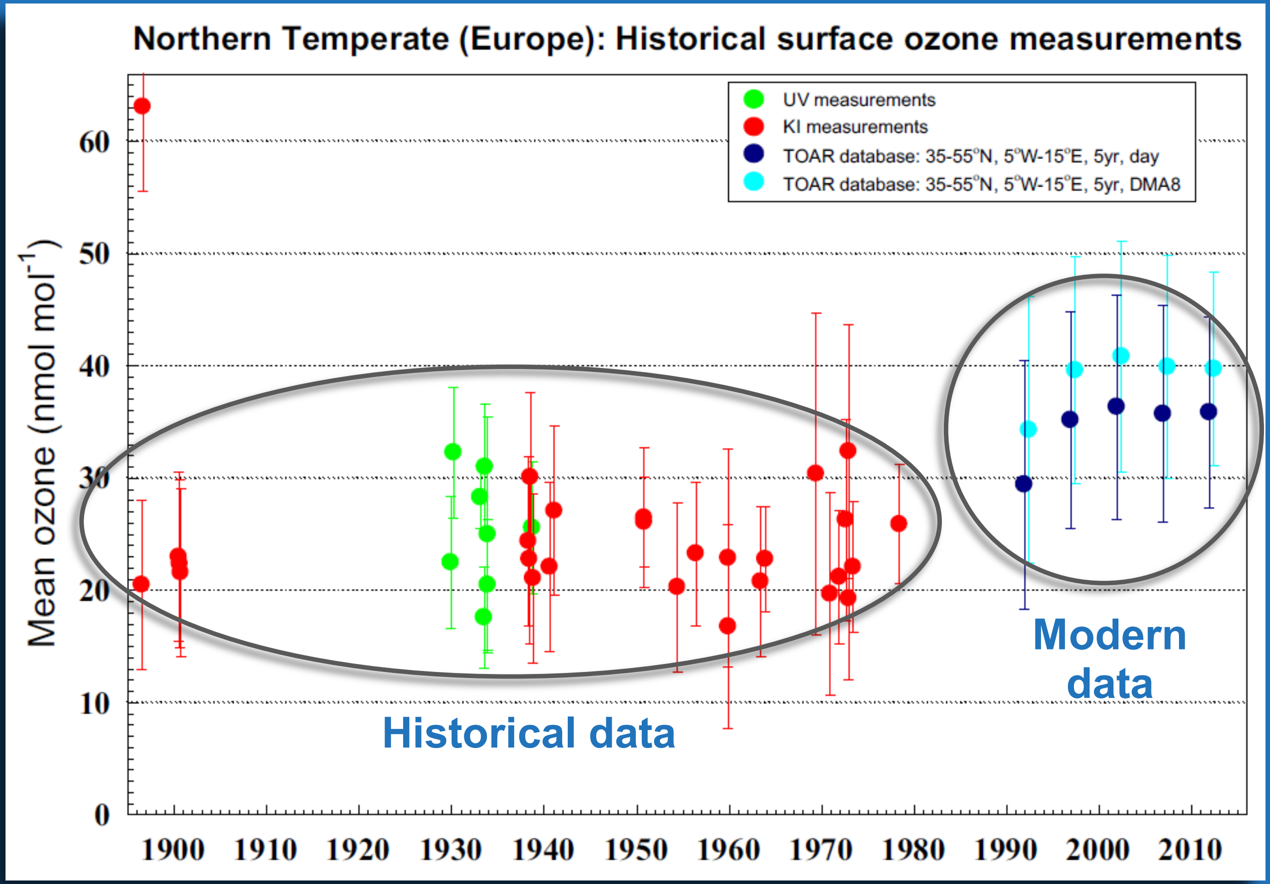
Results from the Tropospheric Ozone Assessment Report

The most extensive evaluation of historical (pre-1975) ozone observations

Ozone has increased at northern mid-latitudes since the mid-20th century, in the range 30-70 %

See *TOAR-Observations* for further details:

Tarasick and Galbally et al. (2019), Tropospheric Ozone Assessment Report: Tropospheric ozone from 1877 to 2016, observed levels, trends and uncertainties. Elem Sci Anth, 7(1)
DOI: http://doi.org/10.1525/elementa.376



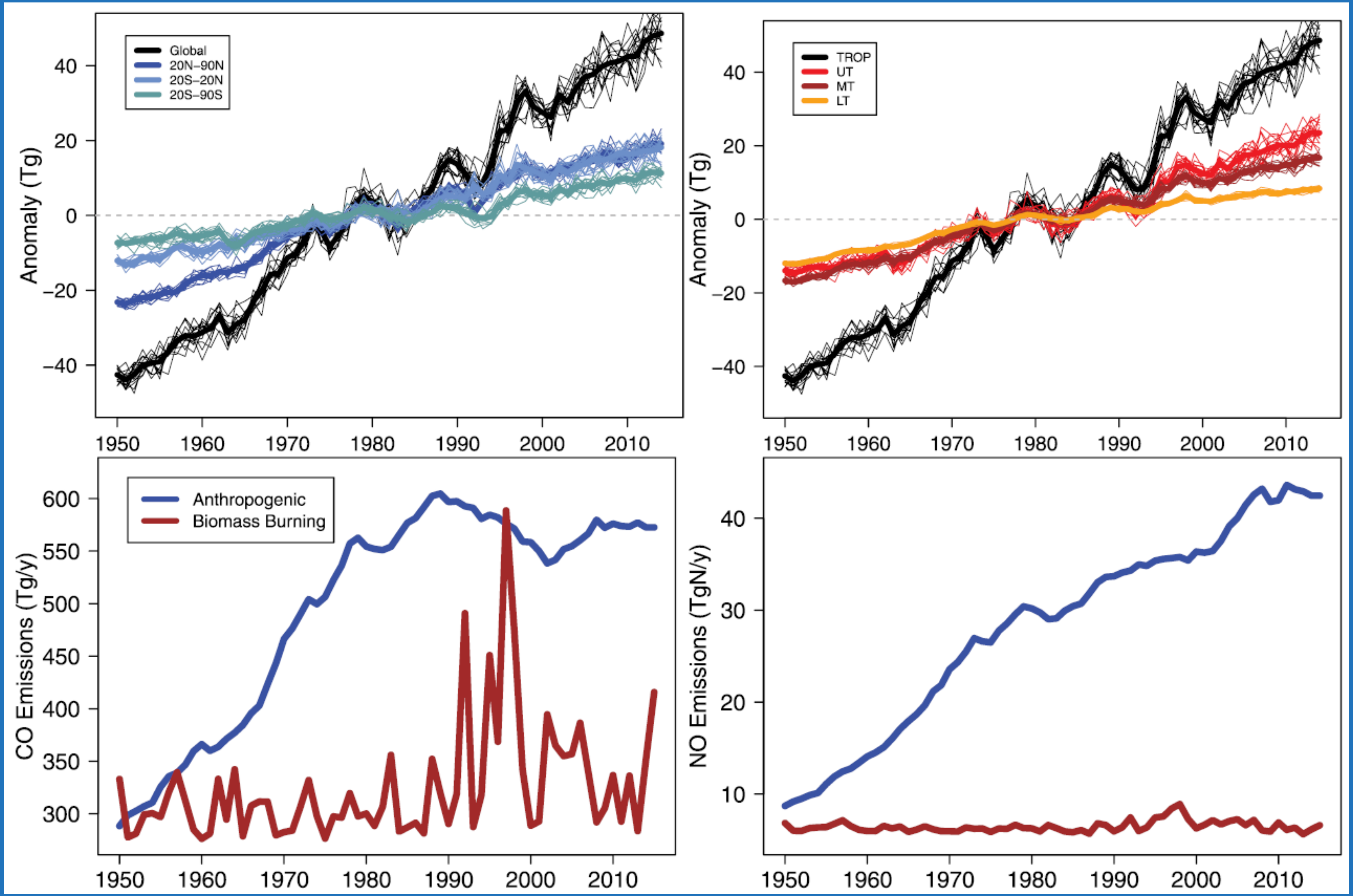
Environ. Res.: Climate **1** (2022) 025008 https://doi.org/10.1088/2752-5295/ac9cc2

ENVIRONMENTAL RESEARCH
CLIMATE

PAPER

Understanding recent tropospheric ozone trends in the context of large internal variability: a new perspective from chemistry-climate model ensembles

Arlene M Fiore[1,2,*], Sarah E Hancock[3,12], Jean-François Lamarque[4], Gustavo P Correa[2], Kai-Lan Chang[5,6], Muye Ru[7,13], Owen Cooper[5,6], Audrey Gaudel[5,6], Lorenzo M Polvani[2,8], Bastien Sauvage[9] and Jerry R Ziemke[10,11]



Global
20N–90N
20S–20N
20S–90S
Anomaly (Tg)
40
20
0
−20
−40
1950
1960
1970
1980
1990
2000
2010
TROP
UT
MT
LT
Anomaly (Tg)
Anthropogenic
Biomass Burning
CO Emissions (Tg/y)
600
550
500
450
400
350
300
NO Emissions (TgN/y)
40
30
20
10

Possible ozone pathway in the 21st Century

A potential Shared Socio-economic Pathway for the 21st Century is SSP3-7.0

- This pathway will lead to an increase in the global tropospheric ozone burden
- Surface ozone will decrease in remote regions due to increased water vapor
- Surface ozone will increase in developing regions with increasing precursor emissions

IOP Publishing Environ. Res. Lett. 17 (2022) 024014 https://doi.org/10.1088/1748-9326/ac4a34

ENVIRONMENTAL RESEARCH LETTERS

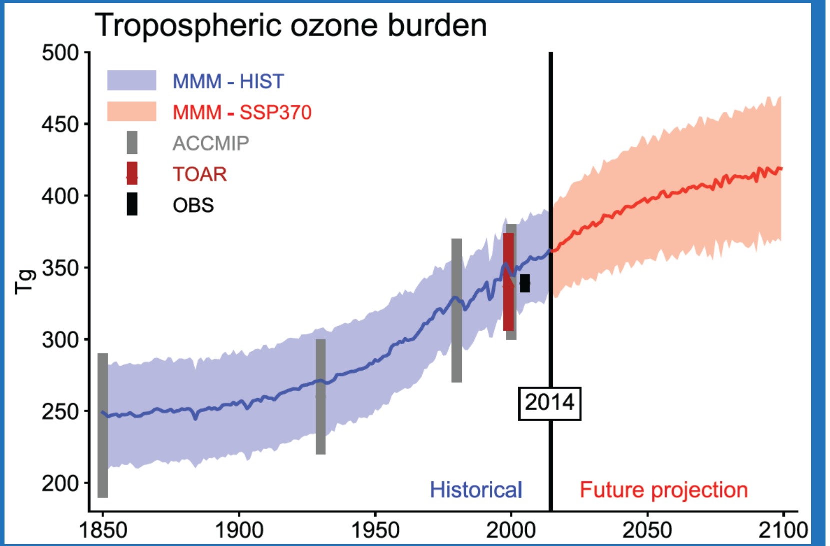
RECEIVED
9 October 2021

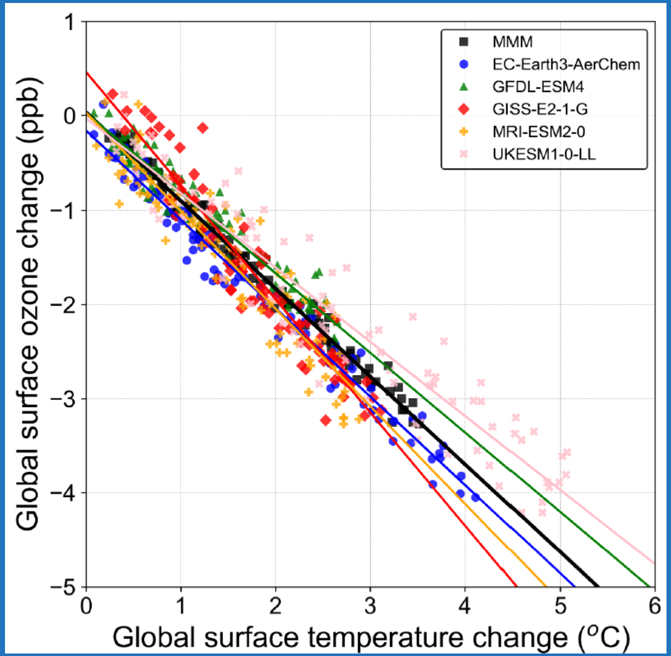
REVISED
5 January 2022

LETTER

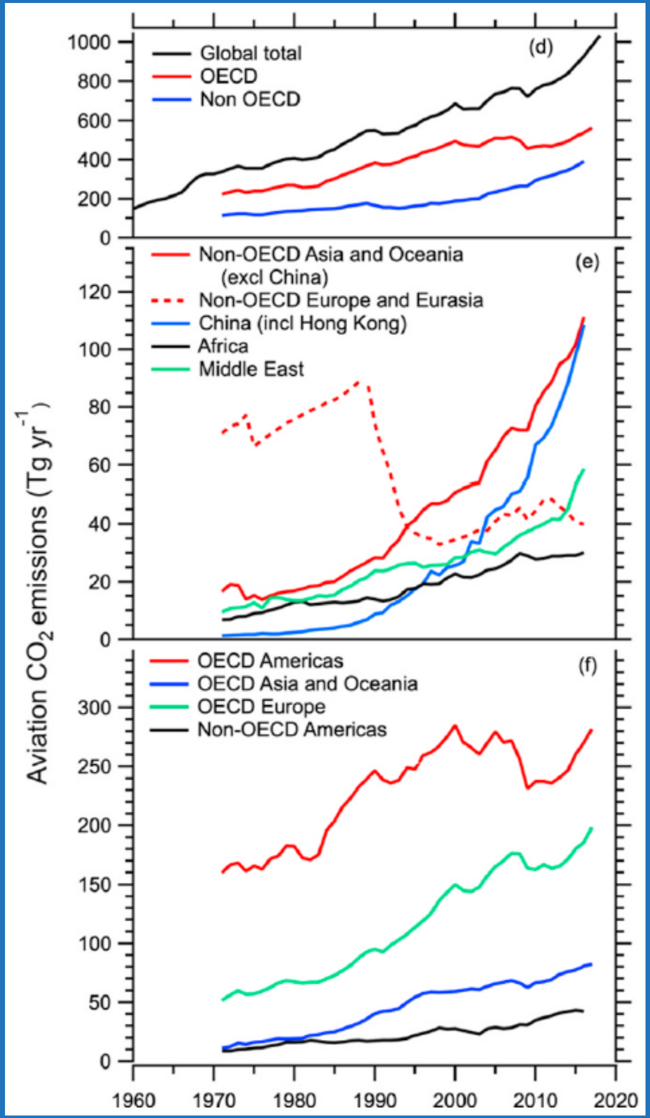
Climate change penalty and benefit on surface ozone: a global perspective based on CMIP6 earth system models

Prodromos Zanis[1,*], Dimitris Akritidis[1], Steven Turnock[2,3], Vaishali Naik[4], Sophie Szopa[5], Aristeidis K Georgoulias[1], Susanne E Bauer[6], Makoto Deushi[7], Larry W Horowitz[4], James Keeble[8,9], Philippe Le Sager[10], Fiona M O'Connor[2], Naga Oshima[7], Konstantinos Tsigaridis[6,11] and Twan van Noije[10]





Global aviation CO_2 emissions doubled from 1990 to 2018.



Atmos. Chem. Phys., 22, 13753–13782, 2022
https://doi.org/10.5194/acp-22-13753-2022

Atmospheric Chemistry and Physics
Open Access
EGU

Global tropospheric ozone trends, attributions, and radiative impacts in 1995–2017: an integrated analysis using aircraft (IAGOS) observations, ozonesonde, and multi-decadal chemical model simulations

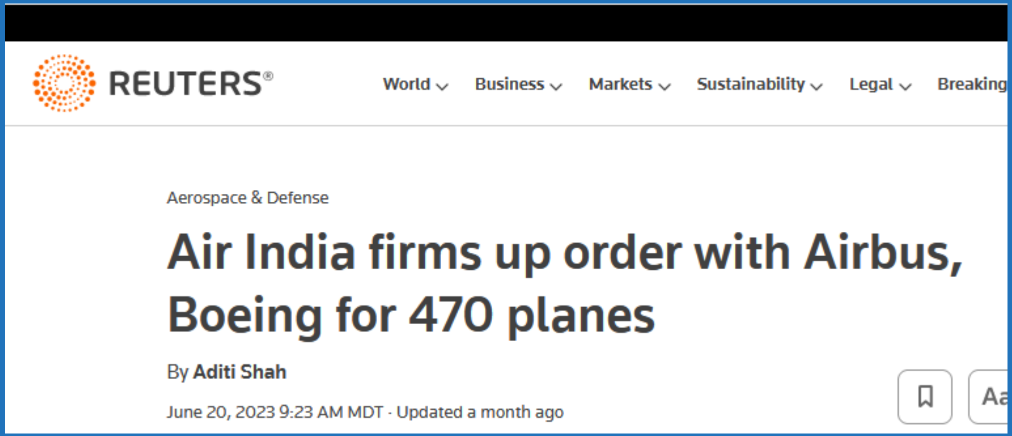
Haolin Wang[1,2], Xiao Lu[1,2], Daniel J. Jacob[3], Owen R. Cooper[4,5], Kai-Lan Chang[4,5], Ke Li[6], Meng Gao[7], Yiming Liu[1,2], Bosi Sheng[1], Kai Wu[8], Tongwen Wu[9,10], Jie Zhang[9,10], Bastien Sauvage[11], Philippe Nédélec[11], Romain Blot[11], and Shaojia Fan[1,2]

A recent GEOS-Chem analysis attributes 66% of the 1995-2017 increase of the global tropospheric ozone burden to aircraft emissions.

Lee, D.S., Fahey, D.W., et al., The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, Atmos. Environ. (2020), doi: https://doi.org/10.1016/j.atmosenv.2020.117834

Aircraft emissions will increase in the coming decades

Model studies are required to understand the impact of future aircraft emissions on the global tropospheric ozone burden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Aerospace & Defense

Air India firms up order with Airbus, Boeing for 470 planes

By Aditi Shah

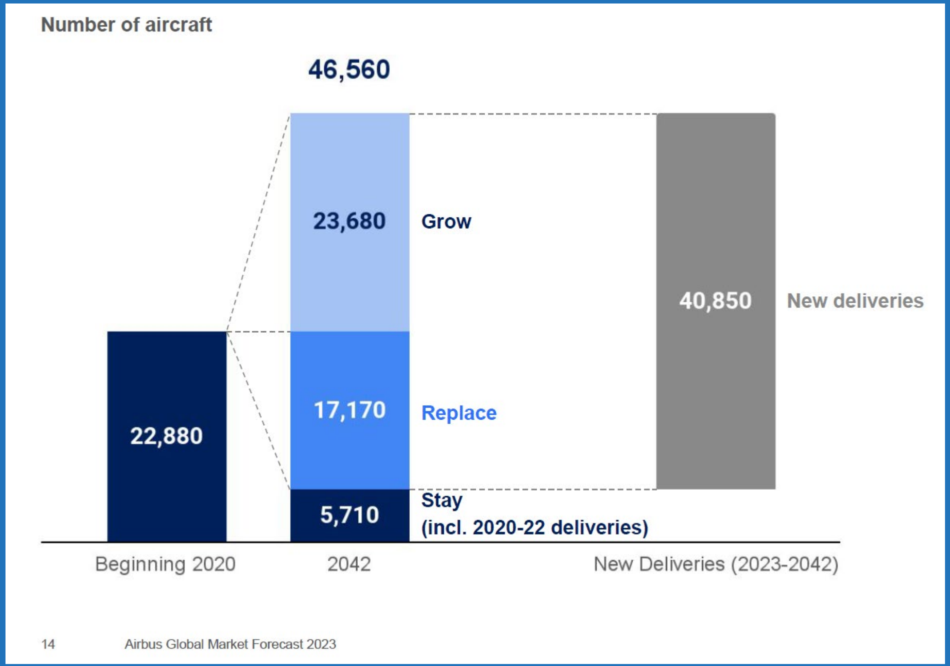
June 20, 2023 9:23 AM MDT · Updated a month ago


CNN BUSINESS Markets Tech Media Calculators Videos

Biggest plane deal in history: Airbus clinches massive order from India's IndiGo

By Anna Cooban, CNN

Published 12:14 PM EDT, Mon June 19, 2023



Global increase in aircraft:

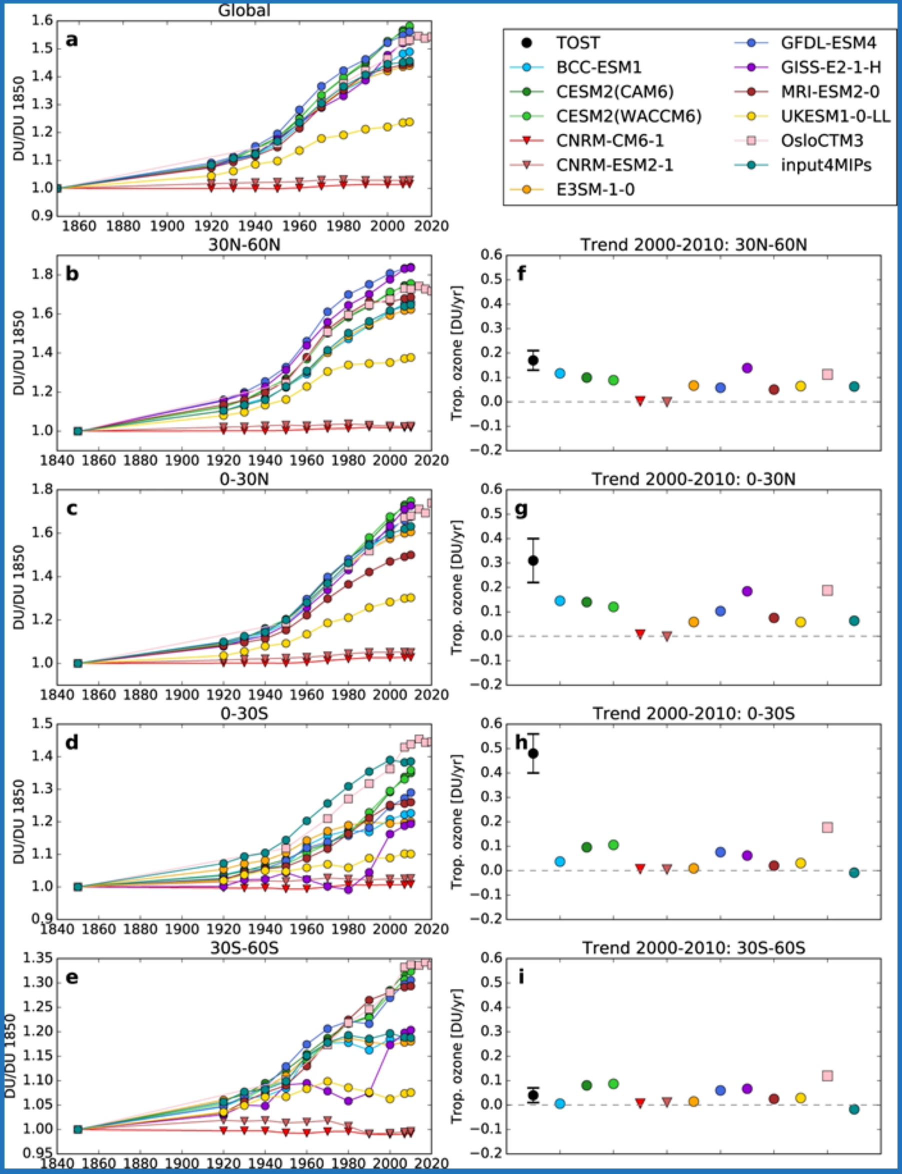
Airbus estimates that the number of in-service commercial aircraft will more than double from 2020 to 2042

-Surface ozone trends at sparse remote monitoring sites do not reflect trends in the free troposphere or the tropospheric column

The balance of evidence from surface sites, commercial aircraft, ozonesondes and satellite products show ozone has increased since the mid-1990s in:

Northern mid-latitudes
Northern tropics
Southern tropics } ~ 3 ppbv per decade

Limited data from the southern mid-latitudes suggest a weak increase



Tropospheric ozone is a short-lived trace gas

1) that originates naturally in the stratosphere, or

2) is produced by photochemical reactions involving sunlight and precursor gases.

Ozone precursor gases:

nitrogen oxides, non-methane volatile organic compounds, methane or carbon monoxide

Natural sources - wildfires, biogenic hydrocarbon emissions, lightning NO_x, and biogenic NO_x emitted from soils

Anthropogenic sources - fossil fuel and biofuel combustion, or crop burning.

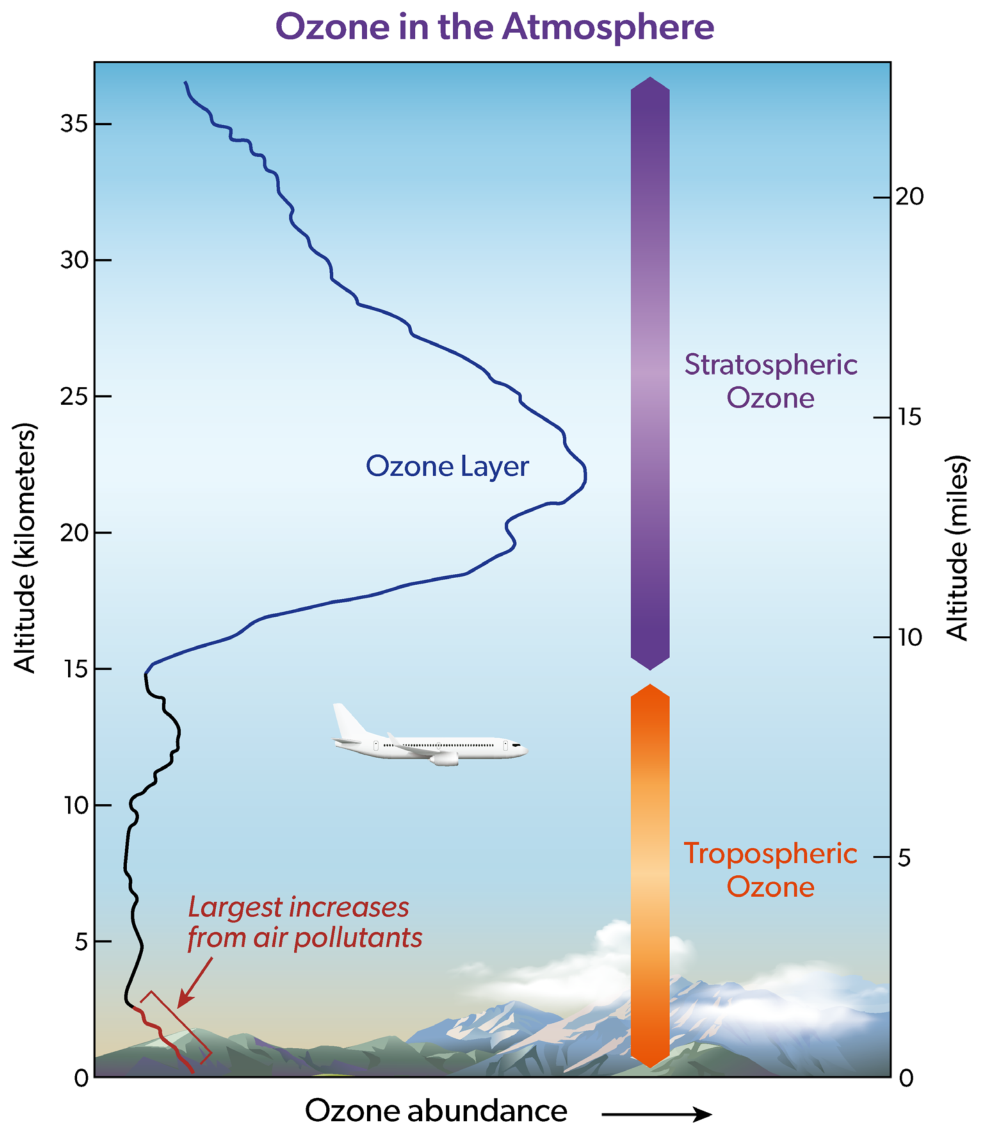


Figure from:

Salawitch R.J., L. A. McBride, C. R. Thompson, E. L. Fleming, R. L. McKenzie, K. H. Rosenlof, S. J. Doherty, D. W. Fahey, Twenty Questions and Answers About the Ozone Layer: 2022 Update, Scientific Assessment of Ozone Depletion: 2022, 75 pp., WMO, Geneva, Switzerland, 2023.

Global CO_2 emissions through 2022

Friedlingstein, P., et al., Global Carbon Budget 2022, Earth Syst. Sci. Data, 14, 4811-4900, 2022
https://doi.org/10.5194/essd-14-4811-2022