

An update on ever-changing global tropospheric ozone trends

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

INTERGOVERNMENTAL PANEL ON Climate change Climate Change 2021 The Physical Science Basis

idcc



IPCC Sixth Assessment Report, 2021



WORLD METEOROLOGICAL ORGANIZATION UNITED NATIONS ENVIRONMENT PROGRAM INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

1990

CLIMATE CHANGE 1995 The Science of Climate Change (2) Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change



CLIMATE CHANGE 2001 The Scientific Basis f Working Group I to the Thi

2001



Working Group I Contribution to the Fourth Assessmen Report of the Intergovernmental Panel on Chimate Chang

2007



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2013

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

- 1990 no estimate
- 1995 $0.4 \pm 0.2 \text{ W m}^{-2}$
- 2001 $0.35 \pm 0.2 \text{ W m}^{-2}$
- 2007 0.35 (0.25 0.65) W m⁻²
- 2013 0.40 \pm 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 \pm 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)



Sat3 1995-2015 (GOME, SCIAMACHY, GOME-II)



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

OMIMLS TCO trend from anomalies



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

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



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

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Guangzhou	-40 -51 -38 -37 -	24 -56 -32 -26	7.3 -66 -23 -11	18 -62 -30 -21 -	-4.2 16 -22	-24 -23 -20 -14	-40 -51 -40 -40 -		
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Shanghai	-4.5 -19 -28 -33	- 22 -24 -37 -34 -	-32 -61 -65 -37	-14 -40 -30 -17 -	-8.4 11 -7.4 -9.4	8.4 -19 -35 -23	-62 -64 -42 -34		
Shenyang	13 31 -38 -4.6	0.36 1.2 -38 -6.9	-28 -51 -37 -9	- 14 -26 -34 2.7 -	-17 17 -4.8 -16	-21 -4.1 -20 -2.1	-69 -75 -78 -47		
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Zhengzhou		40 -29 -45 -48	82 -81 -45 -54 -	21 -54 -45 -29 -	10 88 30 -3.2	-36 -26 -50 -47	76 -68 -70 -57		
Amritsar	9.5 -20 -51 -12	7.2 -15 -48 -26	5.3 -9.1 -53 -35						
Bengaluru	- 30 -11 -43 -19 -				30 -34 -18 -51	18 8.3 22 -15			
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Kolkata	-18 -23 -41 -27	71 -3 -38 -28	-0.43 -11 -48 -18	- 27 36 -26 -50	91 30 12 24	-32 13 -33 -15	22 33 20 20		
Pune	-5.5 -4.1 -17 -18	-22 -19 -28 -24	-40 -37 -44 -31	-49 -60 -75 -63	-16 -23 2.8 27	0.44 -2.8 -17 -9.9	-		
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Seoul	6.7 -34 -22 -23	20 -41 -22 -22	-42 -43 -18 -22	12 -26 -35 -25	8.6 4.5 6	-	-38 -42 -36 -39		
Melbourne	-32 -17 -23 3.8 6.5	-19 -1.4 -19 4.1 21	-9.7 5.8 -15 9.2 56	-8.1 -17 -24 -2 -3.7	-15 1.2 -3 -5.2 0.67	-34 -33 -17 21 11	-40 -51 -18 -38 -33		
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Helsinki	-28 -0.39 -35 -14 -28	-3.8 -6.5 -48 -30 -31	16 -5.1 -54 -39 -36	-32 -42 -59 -45 -34	-1.7 5.6 3.2 -2.2 -1.7	12 -9.1 -32 -14 -17	-43 3.7 -55 -53 -73		
Paris	-58 -9.5 -22 -26	-45 -14 -11 -21	-20 -16 20 -2.4	38 -48 -36 -30			-61 -40 -25 -51		
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Milan	-20 -0.73 -13	-20 -10 -42	7.5 -31 0.79 -26	-3 -10 -43	44 73 10 89	-73 -23 -19 -30	77 22 36 71		
Naples	-13 68 -12 -33	-37 017 -17 -6	-71 -18 -40 3	-22 -14 -58 -46	-95 -16 -19 -96	-23 -46 -53 -63	75 150 -35 -43		
Rome	-0.077 -32 -2.8 -26	9 -18 -10 -14	24 -31 -15 74	-33 -35 -55 -40	-51 11 -0.26 -6.9	6.3 -27 -34 -32	-19 -29 -32 -24		
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Seville	-48 35	-20 -28 -41 -45 -22		-17 -55 -58 -58 -34	-3.2 -2.5 -7.4 -8.7 0.86	45 11 19 25 22	-36 -31 -31 -12 -21		
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Ottawa	-56 -76 74 -21			-23 -32 -24 -32	18 -7 -21 41	-13 -14 -12 -9.4			
Québec City				-14 -25 -39 -36	-1.2 -6.9 0.24 11	-3.1 -19 -7.3 -4	-14 -63 -28 71		
Toronto	-20 -18 -7.7 -16	4		-26 -22 -29 -26	-3.1 -6.8 -2.1 -5.8	-4.9 -10 -15 -9.2	-10 -25 -54 -46		
Vancouver	-15 71 -0.32 -30			14 28 -11 -27	3.7 6.8 2.8 3.4	-9.9 11 -12 -13	-29 0.58 -16 -20		
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Los Angeles	-31 -22 -31	-2 1.4 -5.6	21 12 1.4	-19 -26 -28	-8.3 0.56 -9.1	-20 -21 -25	-12 -27 -32		
New York	-11 -27 -9.9			-9.7 -40 -30	-0.23 2 -3.3	-0.4 -25 -12	-47 -38 8.1		
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São Paulo	-19 -17 -14	-14 -13 -1.6	- 10 -8.5 6.5	-29 -39 -20	13 11 24	-33 -36 -23	-28 -36 -34		
Santiago	-17 -17 -26 -15	8 -1.1 -22 -6	21 9.2 -17 1.7	-11 -28 -31 -15	10 43 42	24 -16 -27	1.7 -4.1 -19		
Bogotá	-17 -20	-5.4 -35 -31	-23 -53 -39	5.8 -51 -18	39 67 17	-2.5 -52 -32	6.2 -27 -10		
Quito	-12 -42 -16	-9 -41 -29	1-1.4 -37 -32	-8.2 -68 -24	14.6 15 14	3.2 -44 -14	-24 -60 -15		
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a) CO abanas

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

Key Points:

 2020 is the only year that both Europe and western North America show strong negative tropospheric ozone 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}, Kai-Lan Chang^{1,2}, Kai-Lan Chang^{1,2}, Kai-Lan Chang^{1,2}, Kai-Lan Chang^{1,2}, Kai-Lan Chang^{1,2}, Kai-Lan Chang^{1,2}, Sophie Godin-Beekmann⁴, Thierry Leblanc⁶, Roeland Van Malderen⁷, Philippe Nédélee⁸, Irina Petropavlovskikh^{1,9}, Kolfgang Steinbrecht¹⁰, René Stübi¹¹, Audre Stübi¹¹, Navid W. Tarasick¹², and Carlos Torres¹³

Impact of the Covid-19 pandemic

Satellite instruments also detected ozone decreases at northern midlatitudes.

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. Kramarova¹, 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. McPeters¹, and Pawan K. Bhartia^{1,5}



Figure 1. (a) Monthly time series of tropospheric column ozone (TCO) (in DU) averaged over the NH for $20^{\circ}N-60^{\circ}N$ 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 © Author(s) 2023. CC BY 4.0 License.





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

Davide Putero¹, Paolo Cristofanelli², Kai-Lan Chang³, Gaëlle Dufour⁴, Gregory Beachley⁵, Cédric Couret⁶, Peter Effertz⁷, Daniel A. Jaffe⁸, Dagmar Kubistin⁹, Jason Lynch⁵, Irina Petropavlovskikh⁷, Melissa Puchalski⁵, Timothy Sharac⁵, Barkley C. Sive¹⁰, Martin Steinbacher¹¹, Carlos Torres¹², and Owen R. Cooper³

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	ОТ
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.





Lassen Volcanic National Park (2000-2021)





Month

- 2000-2019 avg

____ 2020

_____ 2021

10

60

55

50

5

40

35

30

Colorado

Canyonlands National Park (2000-2021)



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

2021-7



Possible ozone pathway in the 21st Century

A potential Shared Socioeconomic 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 midcentury and then decline



WG-I, The Physical Science Basis

SSP5-8.5



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 \pm 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 >35° 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



Parts per billion

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.

Figure 3. Projected changes in

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.

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 Ogino⁶ and J. Jason West^{1*}

nature

geoscience

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.



180°

180°

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 CH₄ 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



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,*}^(D), Sarah E Hancock^{3,12}, Jean-François Lamarque⁴, Gustavo P Correa², Kai-Lan Chang^{5,6}, Muye Ru^{7,13}, Owen Cooper^{5,6}, Audrey Gaudel^{5,6}, Lorenzo M Polvani^{2,8}^(D), Bastien Sauvage⁹ and Jerry R Ziemke^{10,11}



Possible ozone pathway in the 21st Century

A potential Shared Socioeconomic 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

LETTER



OPEN ACCESS

RECEIVED 9 October 2021 REVISED 5 January 2022 Climate change penalty and benefit on surface ozone: a global perspective based on CMIP6 earth system models

Prodromos Zanis^{1,*}, Dimitris Akritidis¹, Steven Turnock^{2,3}, Vaishali Naik⁴, Sophie Szopa⁵, Aristeidis K Georgoulias¹, Susanne E Bauer⁶, Makoto Deushi⁷⁽⁶⁾, Larry W Horowitz⁴, James Keeble^{8,9}, Philippe Le Sager¹⁰, Fiona M O'Connor², Naga Oshima⁷⁽⁶⁾, Konstantinos Tsigaridis^{6,11} and Twan van Noije¹⁰





Global aviation CO₂ emissions doubled from 1990 to 2018.



Atmos. Chem. Phys., 22, 13753–13782, 2022 https://doi.org/10.5194/acp-22-13753-2022 © Author(s) 2022. This work is distributed under the Creative Commons Attribution 4.0 License. Atmospheric Chemistry and Physics

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. Jacob³, Owen R. Cooper^{4,5}, Kai-Lan Chang^{4,5}, Ke Li⁶, Meng Gao⁷, Yiming Liu^{1,2}, Bosi Sheng¹, Kai Wu⁸, Tongwen Wu^{9,10}, Jie Zhang^{9,10}, Bastien Sauvage¹¹, Philippe Nédélec¹¹, Romain Blot¹¹, 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



World
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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



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

By <u>Anna Cooban</u>, 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 CO₂ 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

