ITINERIS

” Ozone near surface measurements (science &techniques)”

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IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-Mission 4 “Education and Research” - Component 2: “From research to business” - Investment 3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”

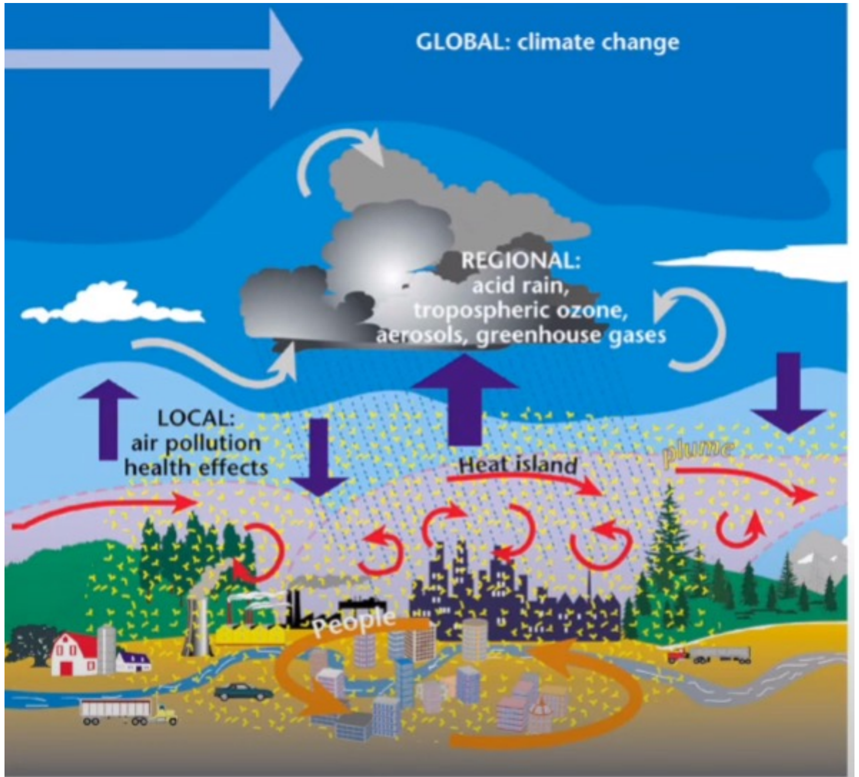
Finanziato dall'Unione europea NextGenerationEU

Ministero dell’Università e della Ricerca

Italiadomani

A TALE OF TWO OZONES
Stratosphere / Ozone Layer
= "good ozone"
15 km
Troposphere / Surface ozone
= "bad ozone"
2 km

Rationale for near-surface ozone measurements



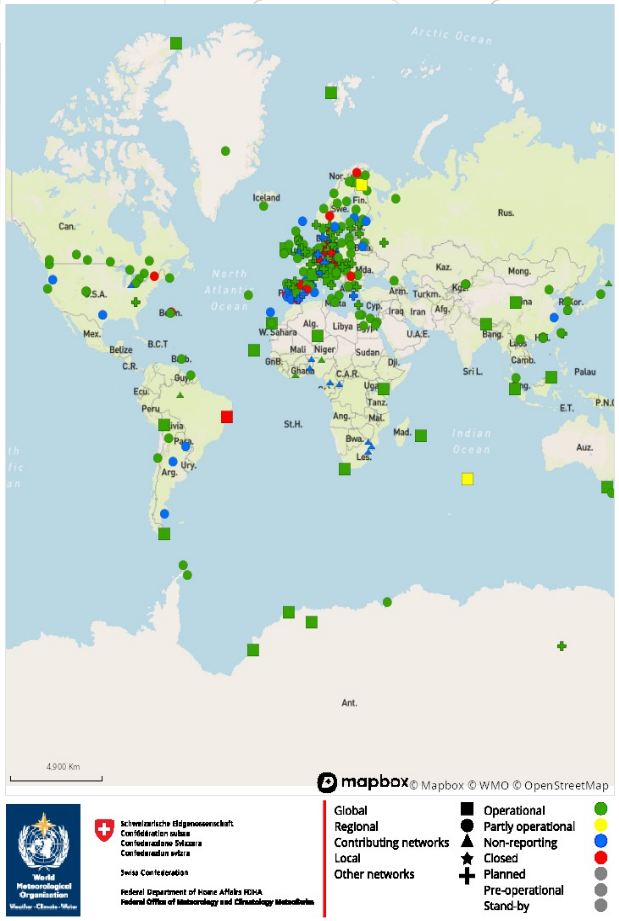
Source: Hidalgo et al.: Advances in Urban Climate Modeling, Trends and Directions in Climate Research: Ann. N.Y. Acad. Sci. 1146: 354–374 (2008).

- ❑ In the lower troposphere, ozone is an air pollutant, treathening human health and ecosystems
- ❑ Elevated ground-level ozone can lead to leaf injury, crop loss and impact on food security
- ❑ In the free (upper) troposphere ozone is a (short-lived) greenhouse gas

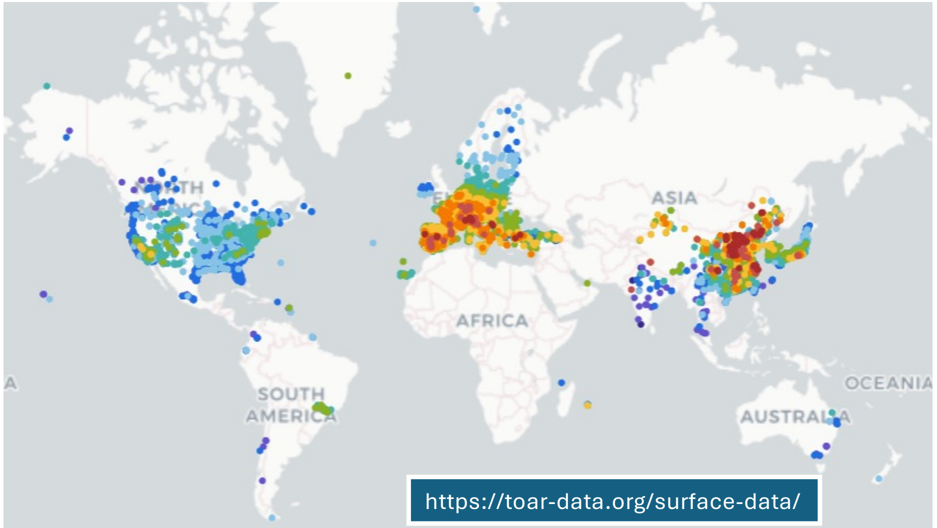
Near-surface ozone

(Global) Stations of the Global Atmosphere Watch Programme

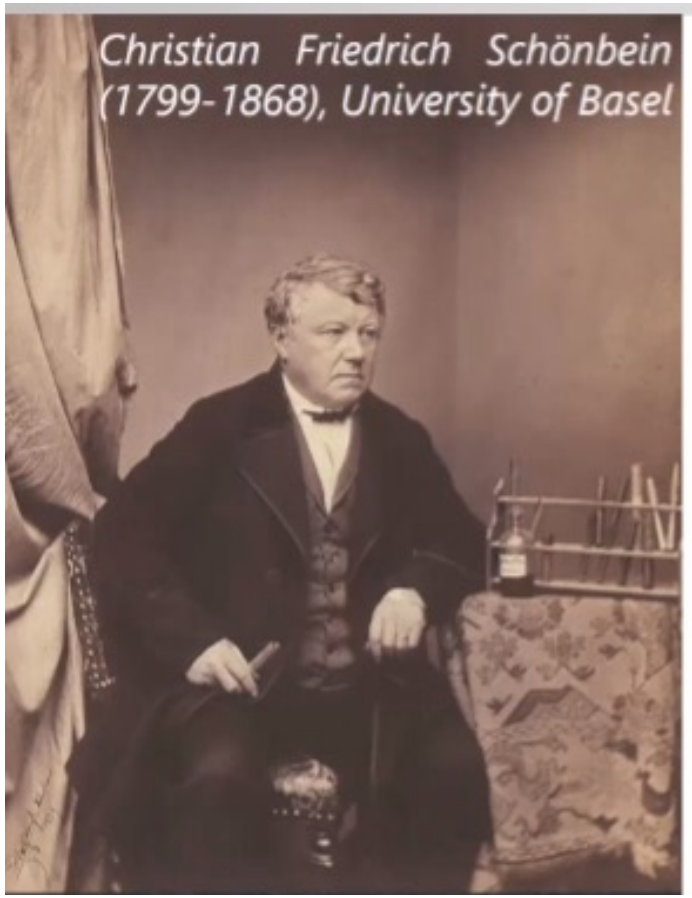
https://gawsis.meteoswiss.ch/GAWSIS/#/

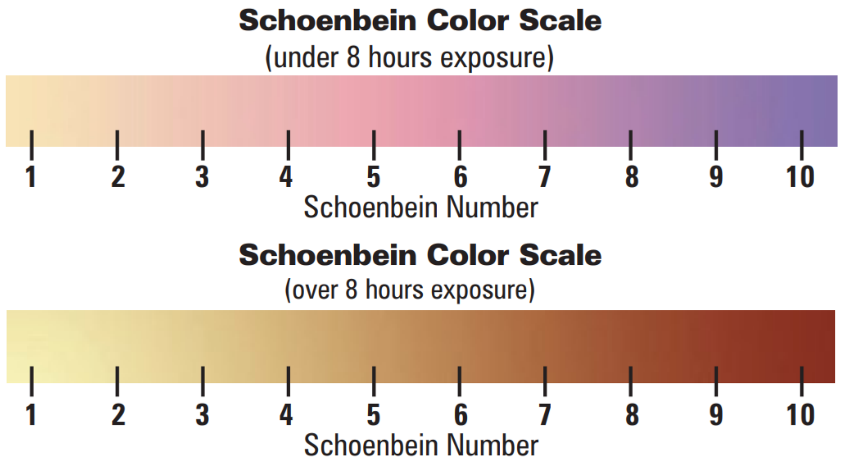


TOAR
tropospheric ozone assessment report



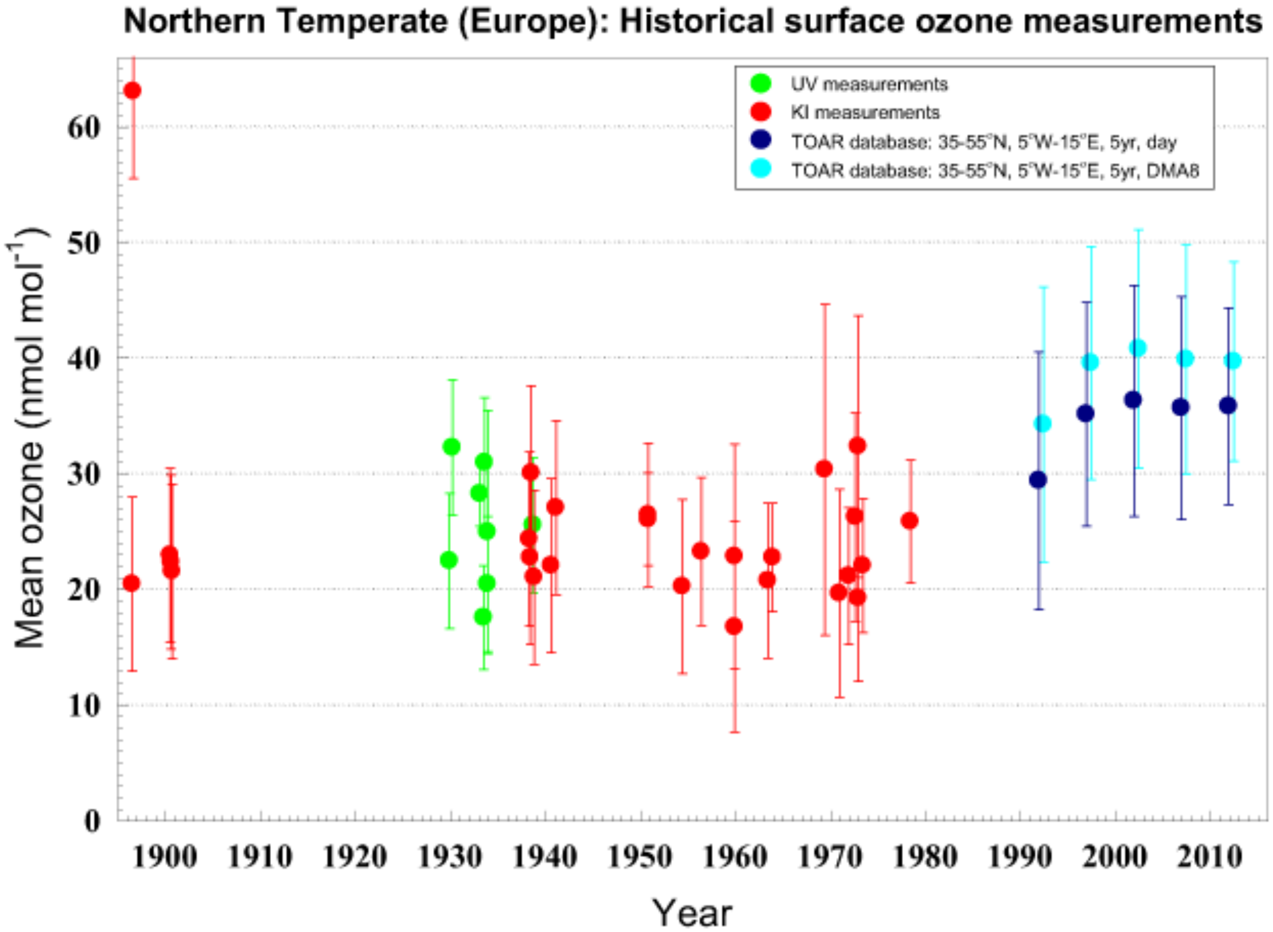
Near-surface ozone





$$O_3 + 2KI + H_2O \rightarrow O_2 + I_2 + 2KOH$$

Near-surface ozone



RESEARCH ARTICLE | DECEMBER 30 2020

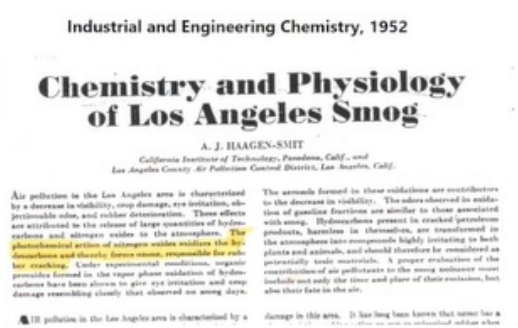
Tropospheric Ozone Assessment Report:
A critical review of changes in the tropospheric ozone burden and budget from 1850 to 2100

Collections: Knowledge Domain: Atmospheric Science , Special Feature: Tropospheric Ozone Assessment Report (TOAR)

A. T. Archibald, J. L. Neu, Y. F. Elshorbany, O. R. Cooper, P. J. Young, H. Akiyoshi, R. A. Cox, M. Coyle,

Near-surface ozone

Arie Haagen-Smit
(1900-1977)

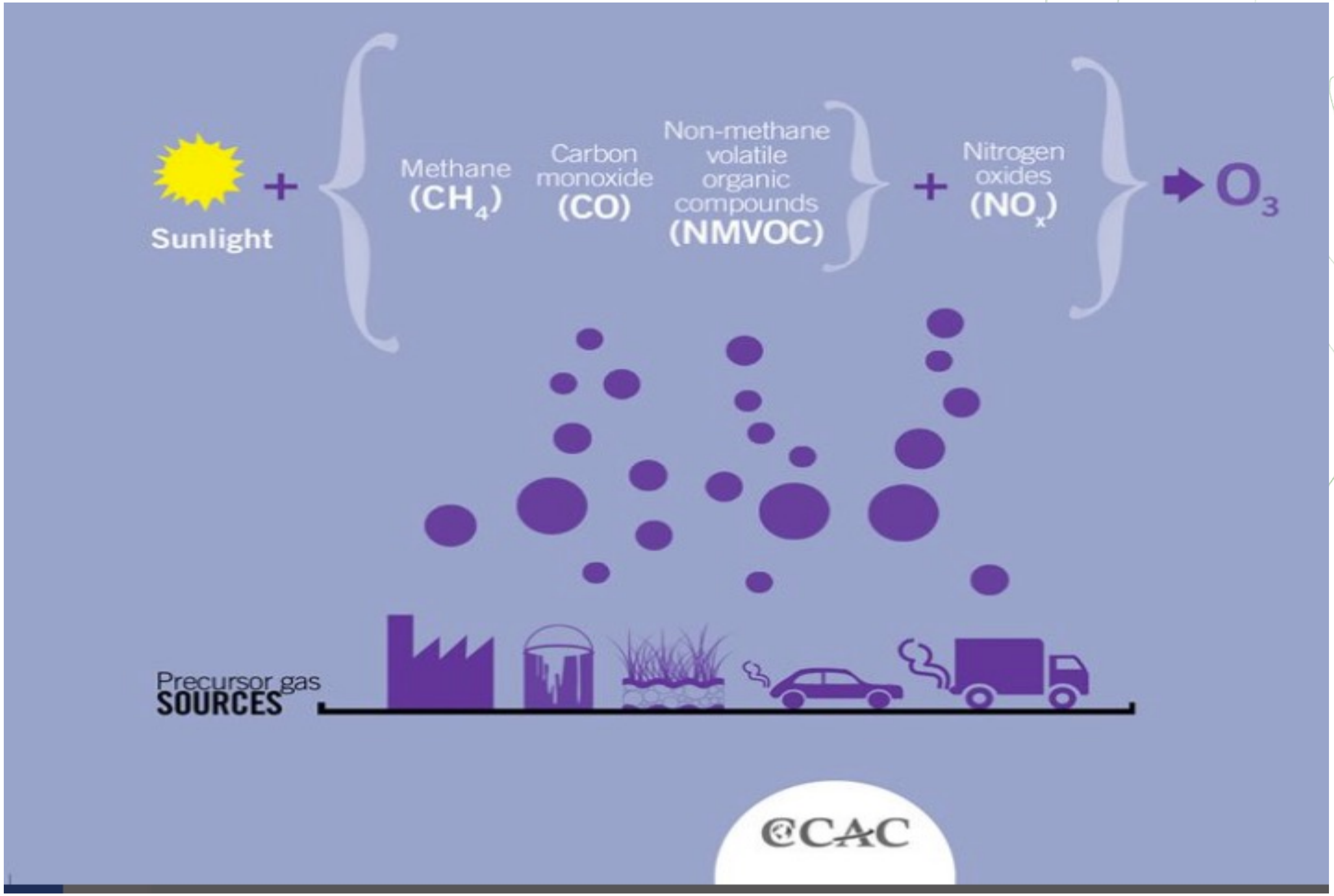


Industrial and Engineering Chemistry, 1952

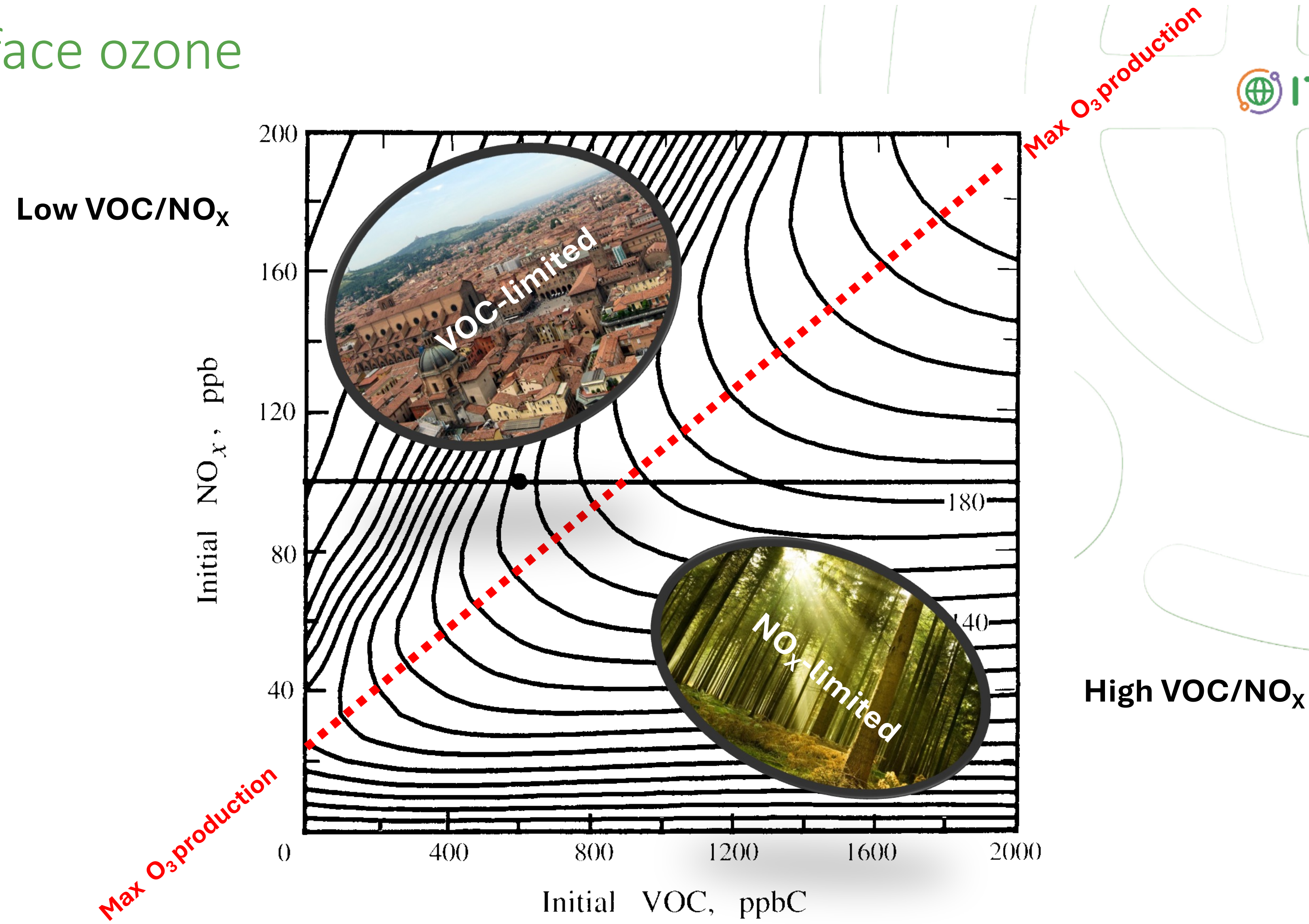
Chemistry and Physiology of Los Angeles Smog

A. J. HAAGEN-SMIT

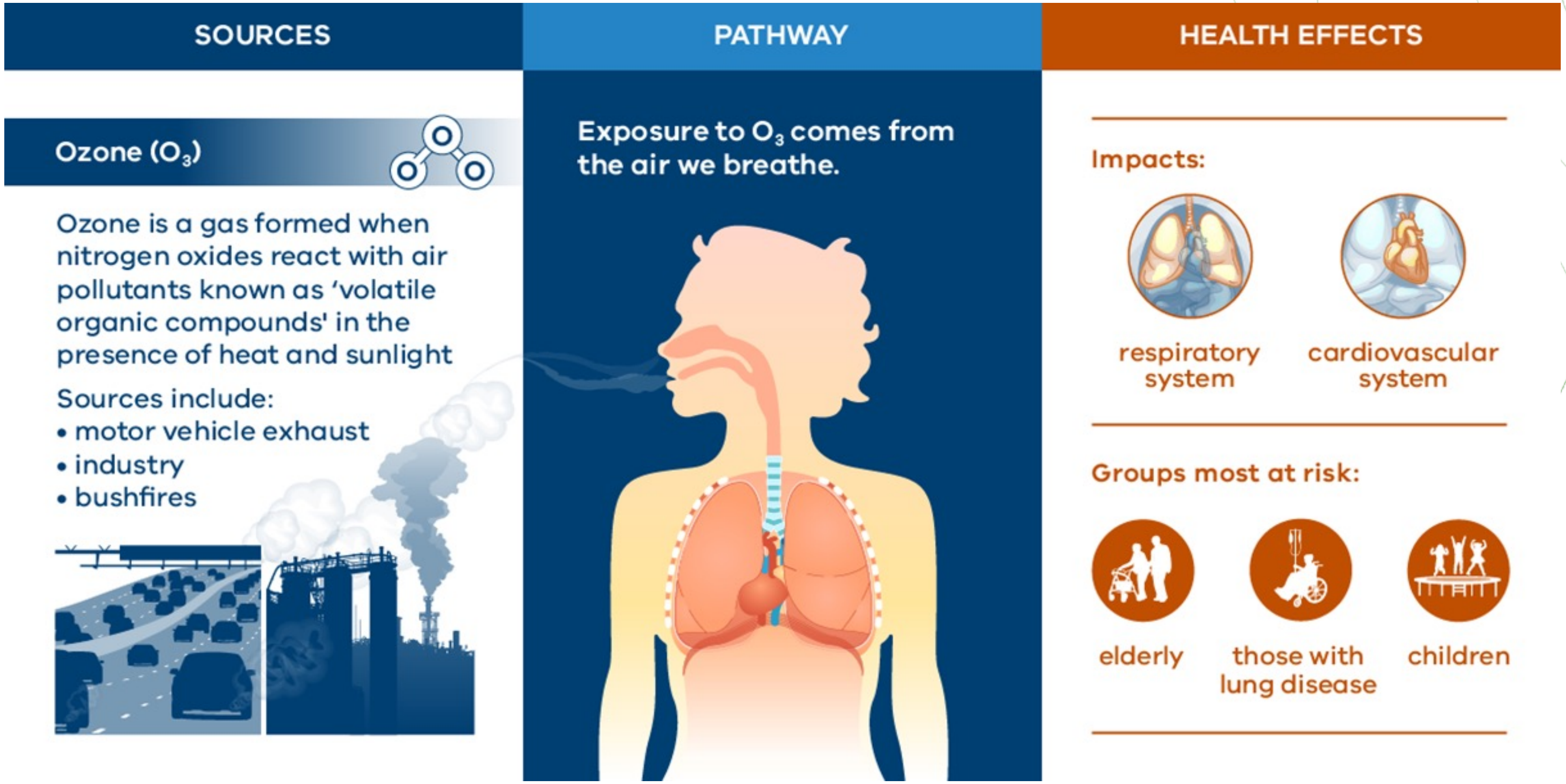
California Institute of Technology, Pasadena, Calif., and Los Angeles County Air Pollution Control District, Los Angeles, Calif.


Sunlight
+
Methane
(CH_4)
Carbon
monoxide
(CO)
Non-methane
volatile
organic
compounds
(NMVOC)
+
Nitrogen
oxides
(NO_x)
O_3
Precursor gas
SOURCES
CCAC

Near-surface ozone



Near-surface ozone



EPA VICTORIA | Environment Protection Authority Victoria

Near-surface ozone

Ozone damage on plants at NCAR's Mesa Lab Cafeteria Patio garden progressed rapidly over several weeks. In the top photo, taken on on August 3, 2015, there was little ozone damage on the potato (far left) and bean (center) plants, but in the bottom photo, taken on September 1, 2015, there is extensive damage.
Danica Lombardozzi/NCAR

Brown patches on these potato leaves are evidence of moderate ozone damage.
Danica Lombardozzi/NCAR

Content on this page edited from a blog post by Danica Lombardozzi, a scientist at the National Center for Atmospheric Research (NCAR). Danica works in the Terrestrial Sciences group of the Climate and Global Dynamics Laboratory, and one of her research interests is the impact of ozone on plants.

What does ozone exposure do to sensitive plants?

When sufficient ozone enters the leaves of a sensitive plant, it can:

- Reduce photosynthesis, which is the process that plants use to convert sunlight to energy to live and grow.
- Slow the plant's growth.
- Increase sensitive plants' risk of:
  - disease
  - damage from insects
  - effects of other pollutants
  - harm from severe weather.

Also, some plants can show visible marks on their leaves when ozone is present under certain conditions.

tulip poplar

https://doi.org/10.5194/egusphere-2024-3742
Preprint. Discussion started: 16 December 2024

EGUsphere
Preprint repository

Ozone causes substantial reductions in the carbon sequestration of managed European forests

Per Erik Karlsson[1], Patrick Büker[2], Sam Bland[3], David Simpson[4], Katrina Sharps[5], Felicity Hayes[5], Lisa

The extensive yellow-ringed brown patches on the top and right side of this snap bean leaf are evidence of severe ozone damage, observed on September 1, 2015.
Danica Lombardozzi/NCAR

Near-surface ozone

B. Ozone target values

Objective	Averaging period	Target value	
Protection of human health	Maximum daily 8-hour mean ([3])	120 µg/m³	not to be exceeded on more than 18 days per calendar year averaged over 3 years ([4]) ([5])
Protection of vegetation	May to July	AOT40 (calculated from 1-hour values)	18 000 µg/m³ × h averaged over 5 years ([4]) From May to July

C. Long-term objectives for ozone (O_3) to be attained by 1 January 2050

Objective	Averaging period	Long-term objective	
Protection of human health	Maximum daily 8-hour mean within a calendar year	100 µg/m³ not to be exceeded on more than 3 days per calendar year (99th percentile)	
Protection of vegetation	May to July	AOT40 (calculated from 1 h values)	6 000 µg/m³ × h

A. Alert thresholds

Pollutant	Averaging period	Alert threshold
Ozone	1 hour	240 µg/m³

B. Information thresholds

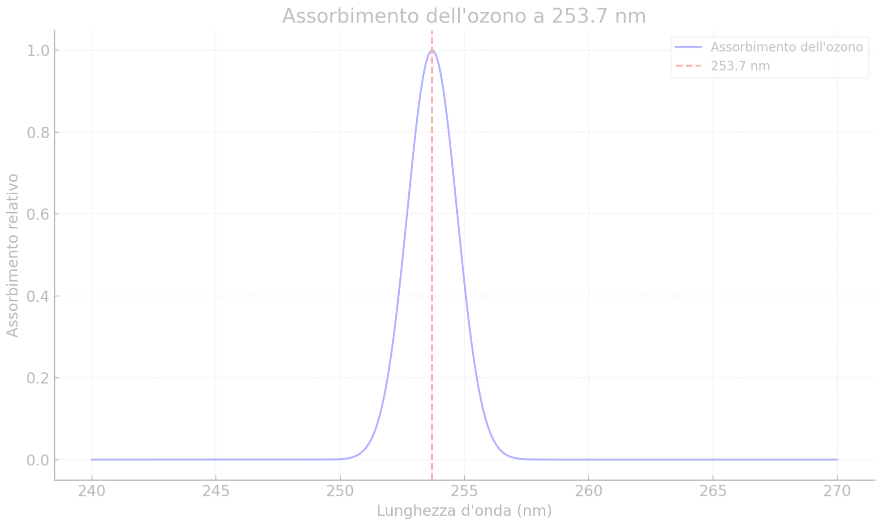
Pollutant	Averaging period	Information threshold
Ozone	1 hour	180 µg/m³

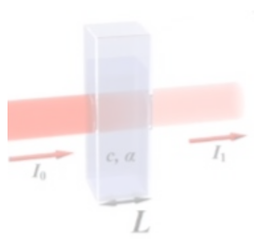
In-situ ozone measurement techniques

- Chemioluminescence: reaction of ozone with ethene to form ethylen oxide

$$O_3 + C_2H_4 \text{ ---> } C_2H_4O + O_2 + h\nu$$ ⟷ *light detector*

- UV-absorption (state-of-art technique).





$$C = \frac{-1}{2\sigma L_{opt}} \frac{T}{T_{std}} \frac{P_{std}}{P} \ln(D)$$

L_{opt} is the optical path length of one of the cells
T_{mes} is the temperature measured in the cells
T_{std} is the standard temperature (273.15 K)
P_{mes} is the pressure measured in the cells
P_{std} is the standard pressure (101.325 kPa)
D is the product of transmittances of the two cells:

$$D = T1 \cdot T2$$

with the transmittance (T) of one cell defined as

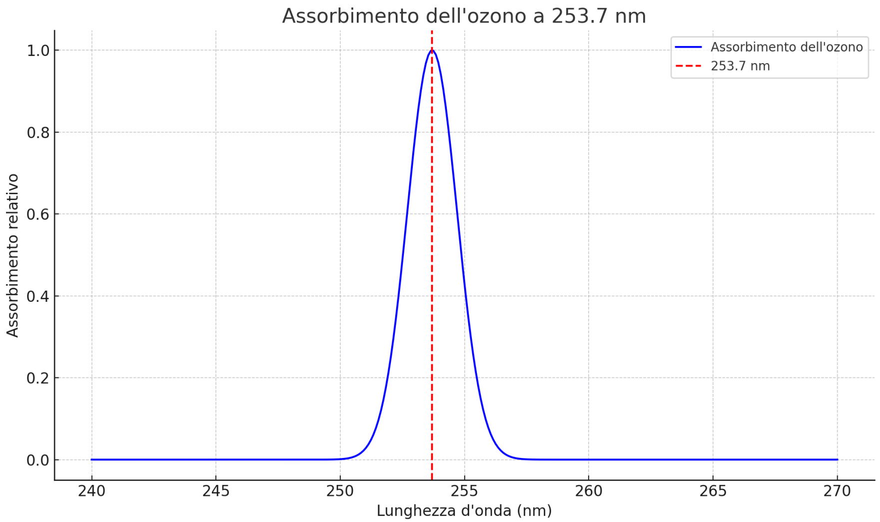
$$T = \frac{I_{ozone}}{I_{air}}$$

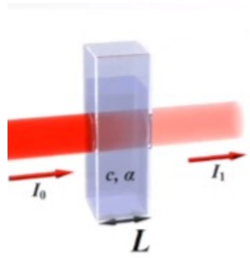
In-situ ozone measurement techniques

- Chemioluminescence: reaction of ozone with ethene to form ethylen oxide

$$O_3 + C_2H_4 \dashrightarrow C_2H_4O + O_2 + h\nu$$ ⟷ *light detector*

- **UV-absorption (state-of-art technique).**





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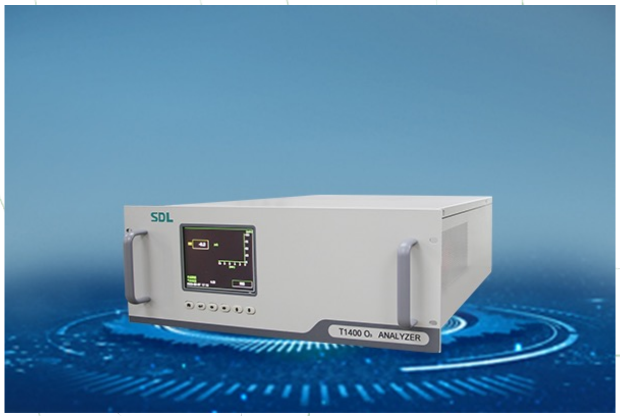
In-situ ozone measurement techniques



In-situ ozone measurement techniques

- Despite other atmospheric species, no large changes in the measurement techniques in the past decades

? – 1995: 49/49PS Series

- Resolution 1 ppb
- Only analog output
- No remote control
- Significantly poorer performance compared to newer models

1996 – 2007: 49C/49C-PS Series

- Resolution 0.1 ppb
- RS-232 and analog output
- Remote control
- Better performance compared to 49-series

2008 – 2022(?): 49i/49i-PS Series

- Resolution 0.1 ppb
- Ethernet, RS-232 and analog output
- Remote access and control
- No further improvement regarding performance to 49C-series

2019 – ?: 49iQ/49iQ-PS Series

- Resolution 0.1 ppb
- Ethernet, RS-232 and analog output
- Remote access and control
- Cheaper components, no further improvement regarding performance to 49i-series

Zellweger C., “measurement of tropospheric ozone”, GAWTEC Webinar Series. https://www.youtube.com/watch?v=_DksbpztnQU

In-situ ozone measurement techniques

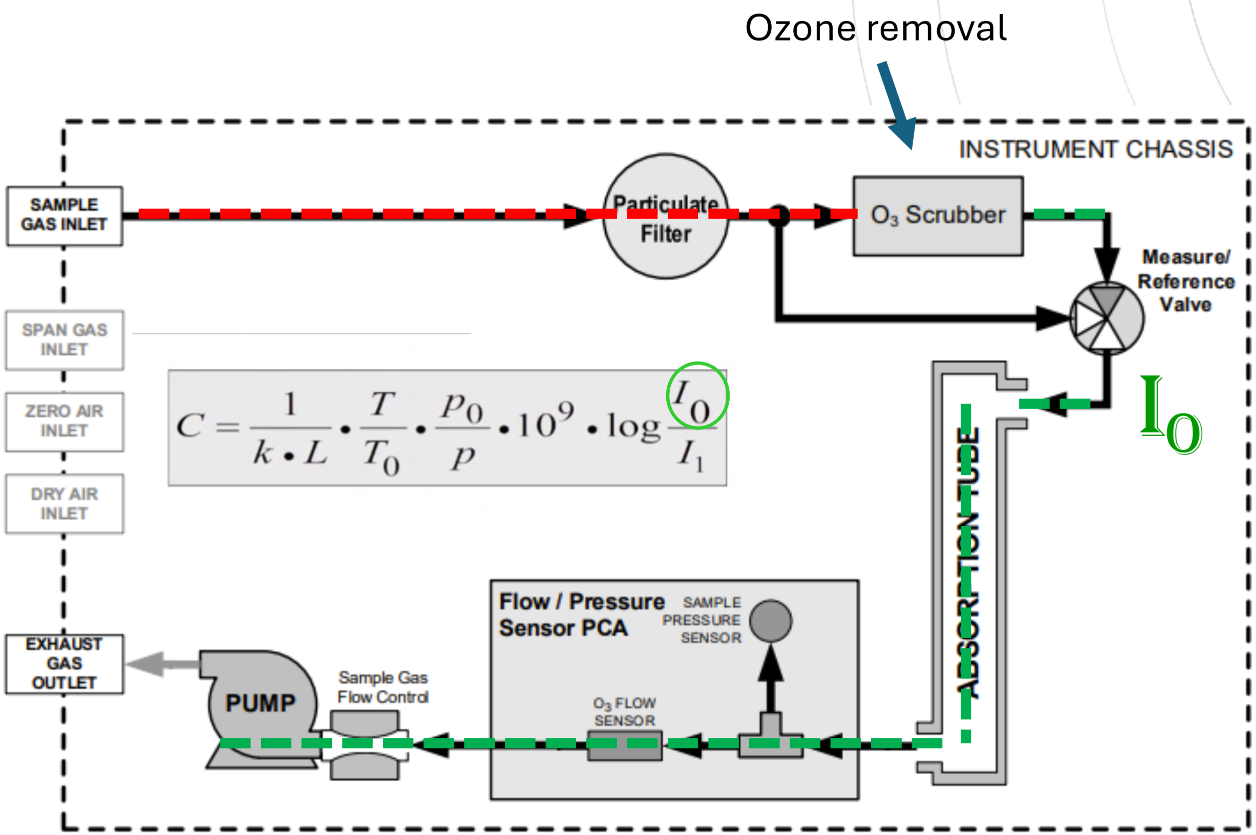


Figure 2-18. T400 Pneumatic Diagram – Basic Unit

In-situ ozone measurement techniques

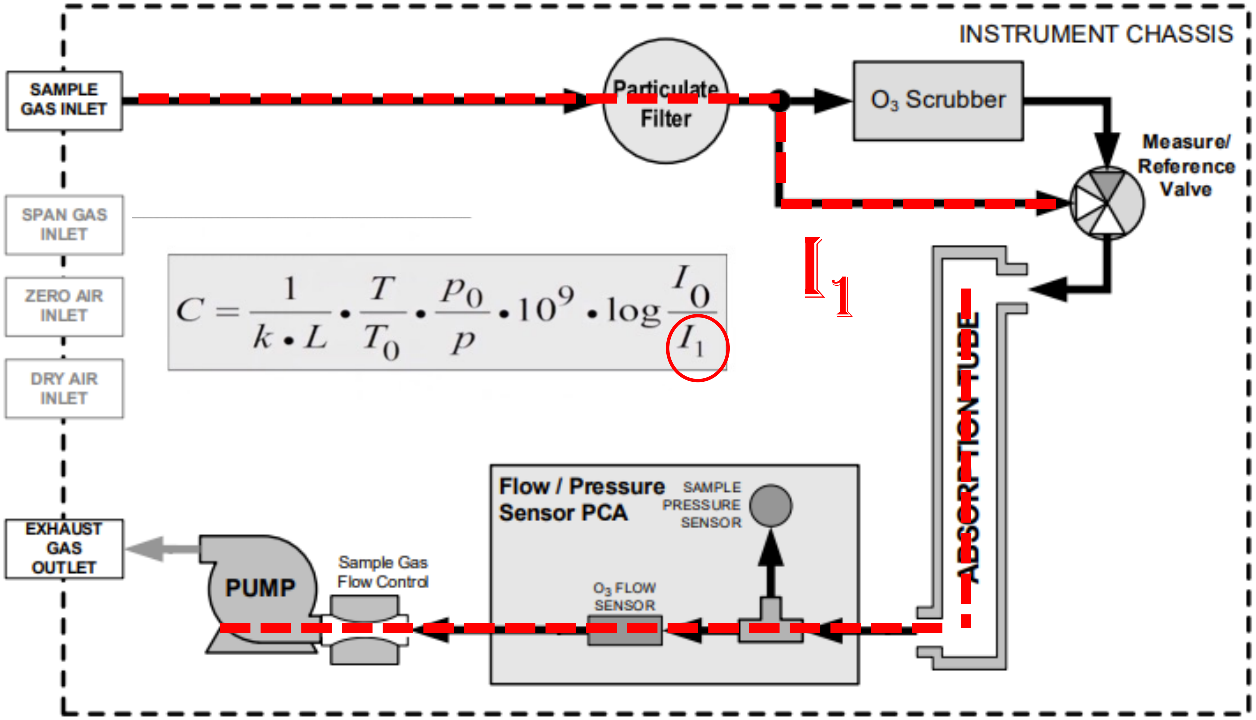
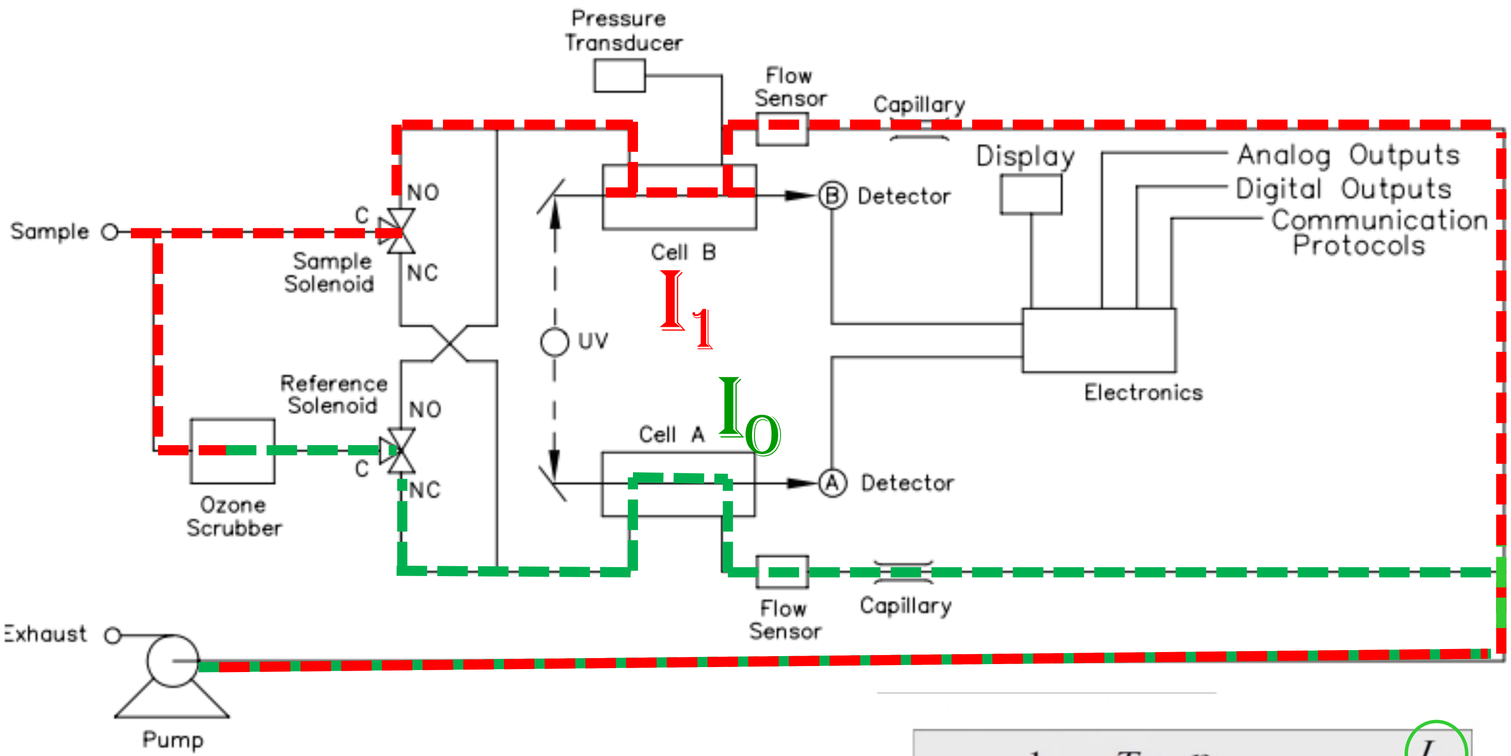


Figure 2-18. T400 Pneumatic Diagram – Basic Unit

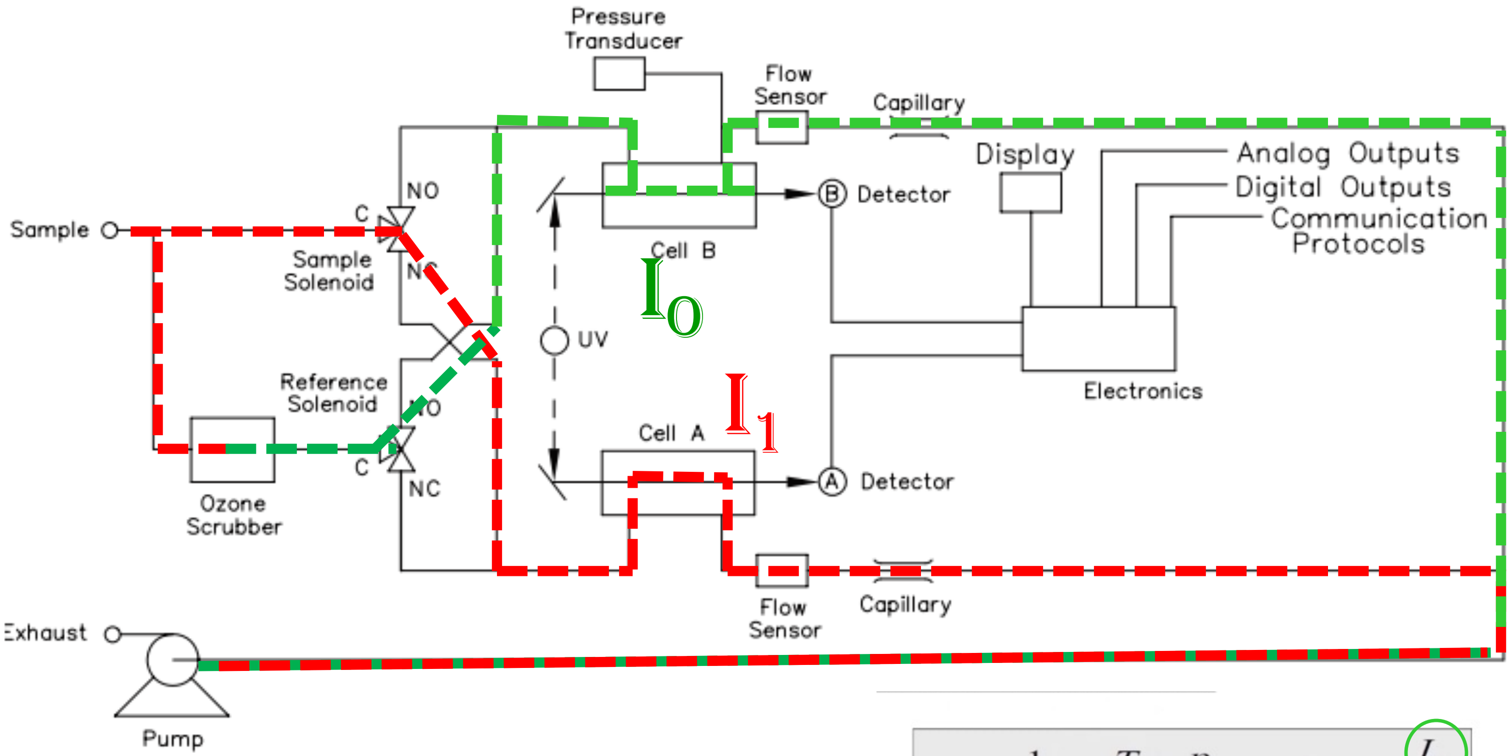
In-situ ozone measurement techniques



$$C = \frac{1}{k \bullet L} \bullet \frac{T}{T_0} \bullet \frac{p_0}{p} \bullet 10^9 \bullet \log \frac{I_0}{I_1}$$

Figure 1-1. Model 49*i* Flow Schematic

In-situ ozone measurement techniques



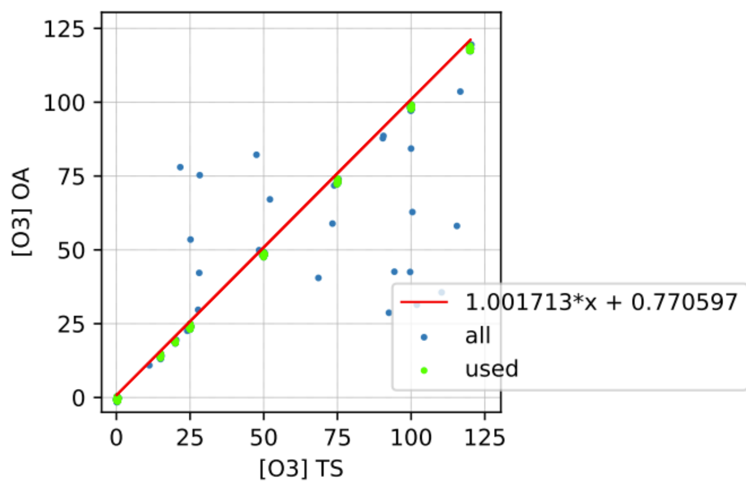
$$C = \frac{1}{k \bullet L} \bullet \frac{T}{T_0} \bullet \frac{p_0}{p} \bullet 10^9 \bullet \log \frac{I_0}{I_1}$$

Figure 1-1. Model 49*i* Flow Schematic

In-situ ozone measurement techniques

- ❑ Calibrations should be performed every ~12 months
- ❑ A Transfer Standard (TS) can be used to generate known ozone levels
- ❑ TS to be traceable to a SRP (Standard Reference Photometer): calibration certificate must be available
- ❑ Pressure sensors must be also calibrated. Check flows.

TSmean	TSstd	OAmean	OAstd	predicted	residual	deviation
0.139	0.132	-0.970	0.544	-0.157	0.296	-1.109
74.289	0.128	73.360	0.314	74.274	0.015	-0.929
49.458	0.086	48.460	0.276	49.340	0.118	-0.998
99.195	0.086	98.260	0.347	99.208	-0.013	-0.935
24.640	0.142	23.540	0.364	24.386	0.253	-1.100
118.983	0.112	117.900	0.219	118.875	0.109	-1.083
14.684	0.122	13.970	0.374	14.803	-0.120	-0.714
0.077	0.132	-0.640	0.310	0.173	-0.096	-0.717
24.564	0.094	23.800	0.283	24.647	-0.082	-0.764
99.112	0.116	98.220	0.214	99.168	-0.056	-0.892
49.463	0.102	48.670	0.215	49.550	-0.087	-0.793
74.349	0.148	73.440	0.398	74.354	-0.005	-0.909
19.670	0.133	18.910	0.298	19.750	-0.080	-0.760
119.026	0.098	118.180	0.442	119.155	-0.129	-0.846
0.130	0.132	-0.730	0.385	0.083	0.047	-0.860
49.497	0.158	48.580	0.447	49.460	0.037	-0.917
24.660	0.140	23.930	0.297	24.777	-0.117	-0.730
74.299	0.094	73.460	0.332	74.374	-0.075	-0.839
99.111	0.094	97.940	0.310	98.888	0.224	-1.171
119.008	0.088	118.110	0.359	119.085	-0.077	-0.898
-0.029	0.138	-0.680	0.376	0.133	-0.162	-0.651



In-situ ozone measurement techniques

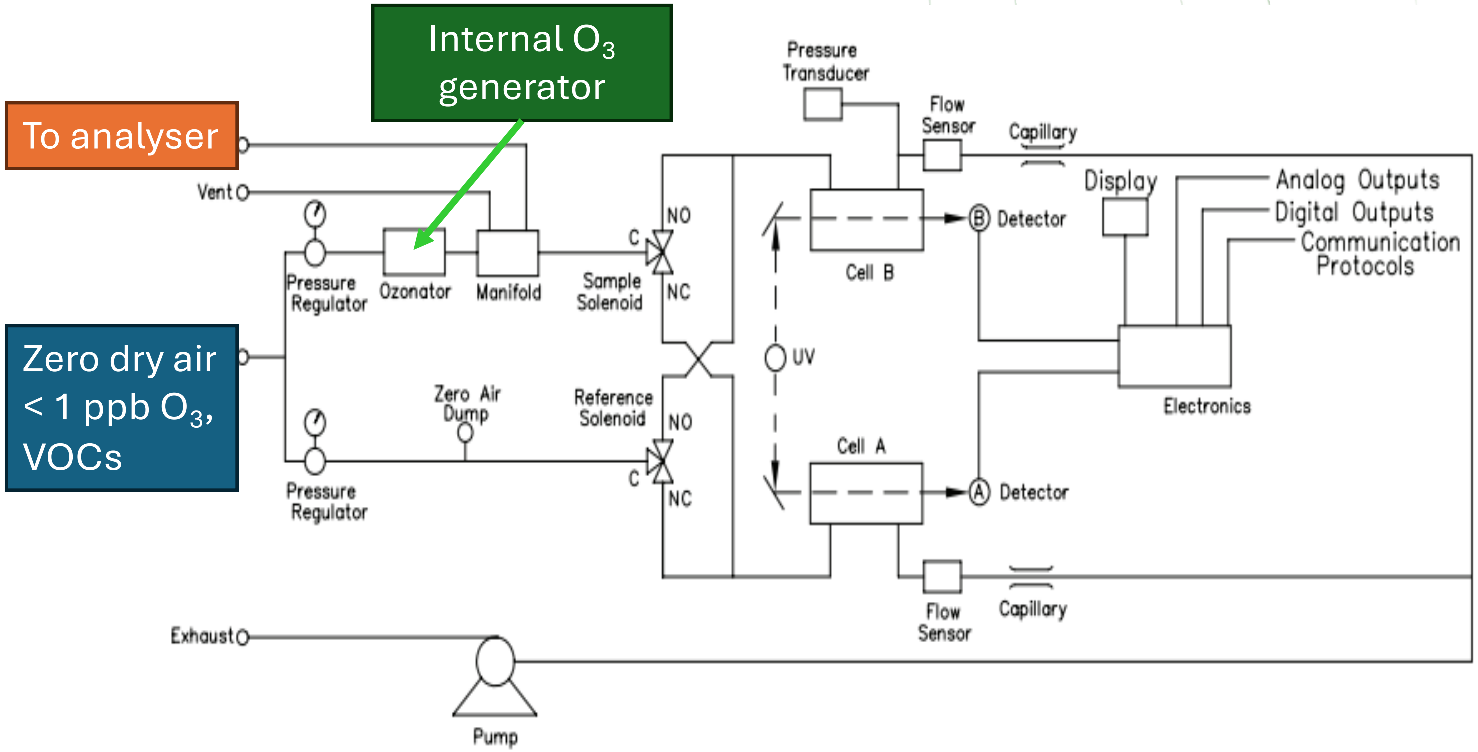


Figure 1-1. Model 49*i* Primary Standard Flow Schematic

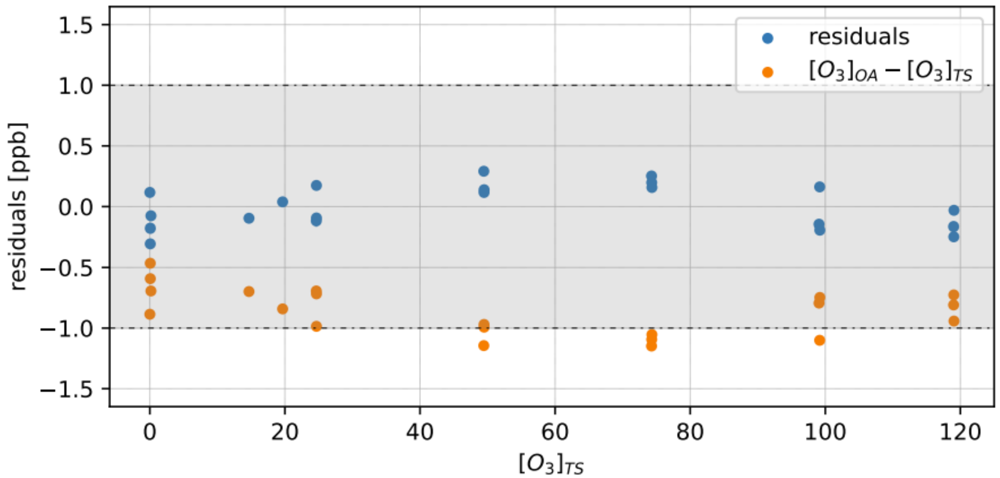
In-situ ozone measurement techniques

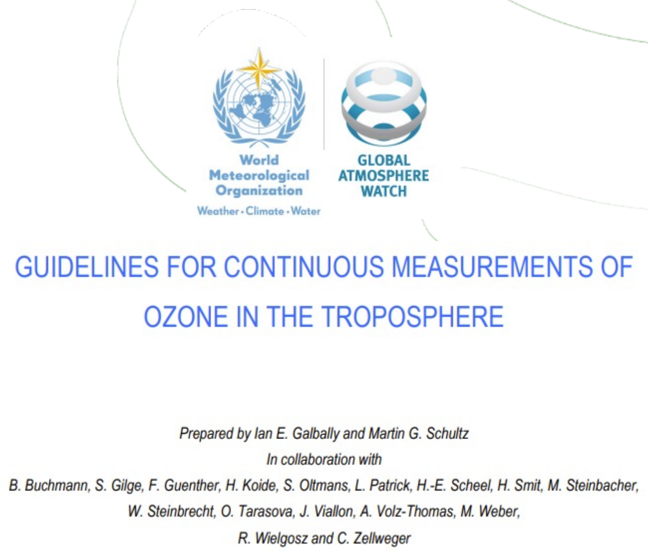
❑ Calibration equation

```
compensation equation to obtain unbiased concentration
[O3unbiased]=([OA]*1.002)+0.771
```

❑ Uncertainty calculation (see DOI:10.1029/2003JD003710)

```
Ulinearity: Residual standard deviation          = 0.177
Urepeat = sqrt(Unoise^2 + Ulinearity^2)          = 0.407
Udrift = sqrt(0.58^2+(0.0025*C)^2)               = 0.632
U = sqrt(Urepeat^2+Udrift^2)                     = 0.751
C                                                = 100.0
```

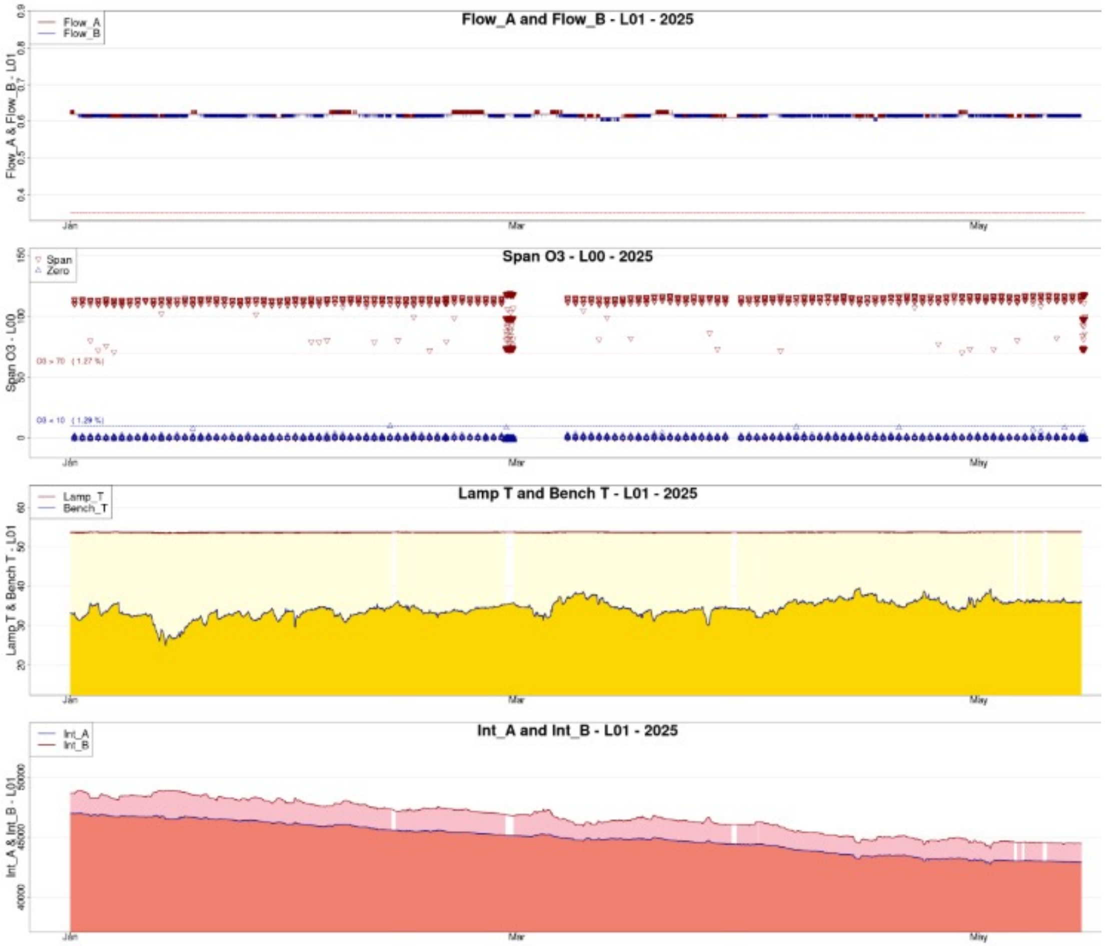



World Meteorological Organization
Weather · Climate · Water
GLOBAL ATMOSPHERE WATCH

GUIDELINES FOR CONTINUOUS MEASUREMENTS OF OZONE IN THE TROPOSPHERE

Prepared by Ian E. Galbally and Martin G. Schultz
In collaboration with
B. Buchmann, S. Gilge, F. Guenther, H. Koide, S. Oltmans, L. Patrick, H.-E. Scheel, H. Smit, M. Steinbacher, W. Steinbrecht, O. Tarasova, J. Viallon, A. Volz-Thomas, M. Weber, R. Wielgosz and C. Zellweger

In-situ ozone measurement techniques



Low flow -> pump problems; check capillaries

Span/Zero check -> leaks or check scrubber efficency

High T -> stability and integrity issues

Lamp intensity -> check cells, to regulate intensities

In-situ ozone measurement techniques

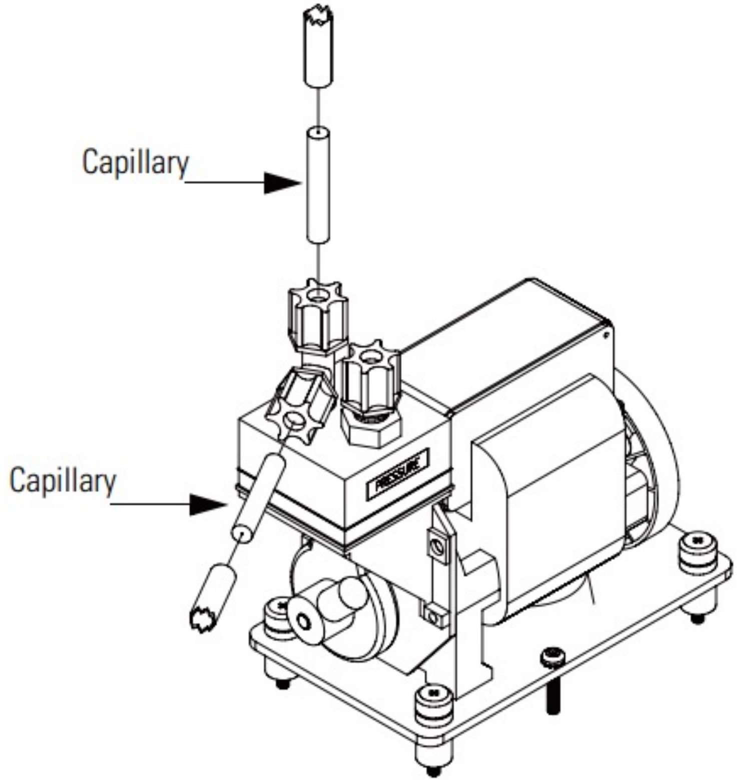


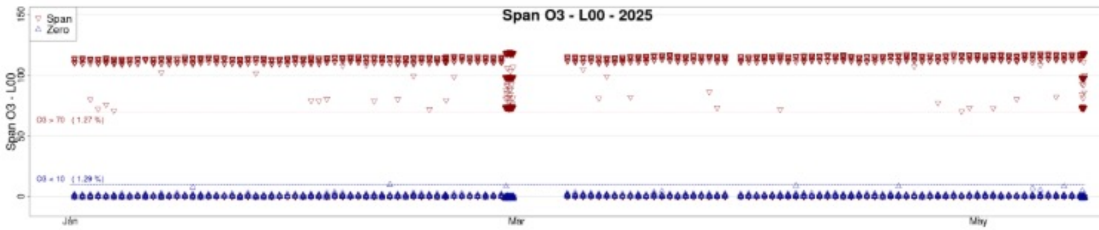
Figure 5-1. Capillary Location

Capillaries limit and stabilize the gas flow (1-3 lt/min) into the measurement system. Maintain constant pressure conditions and residence time within the UV cell.

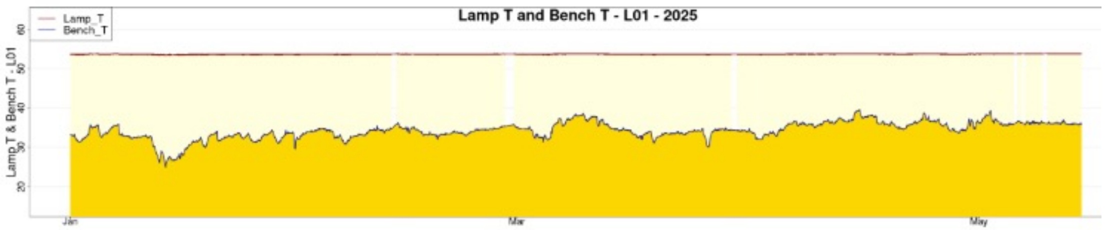
!!!Pump should be regularly mantained (diaphragm change every 1 yr)!!!

In-situ ozone measurement techniques

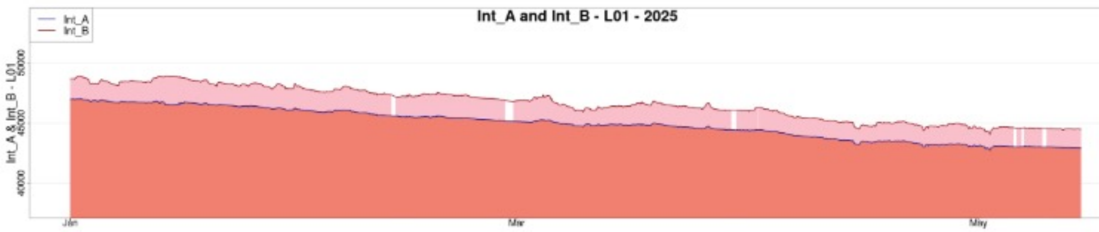
Low flow -> pump problems; check capillaries



Span/Zero check -> leaks or check scrubber efficency

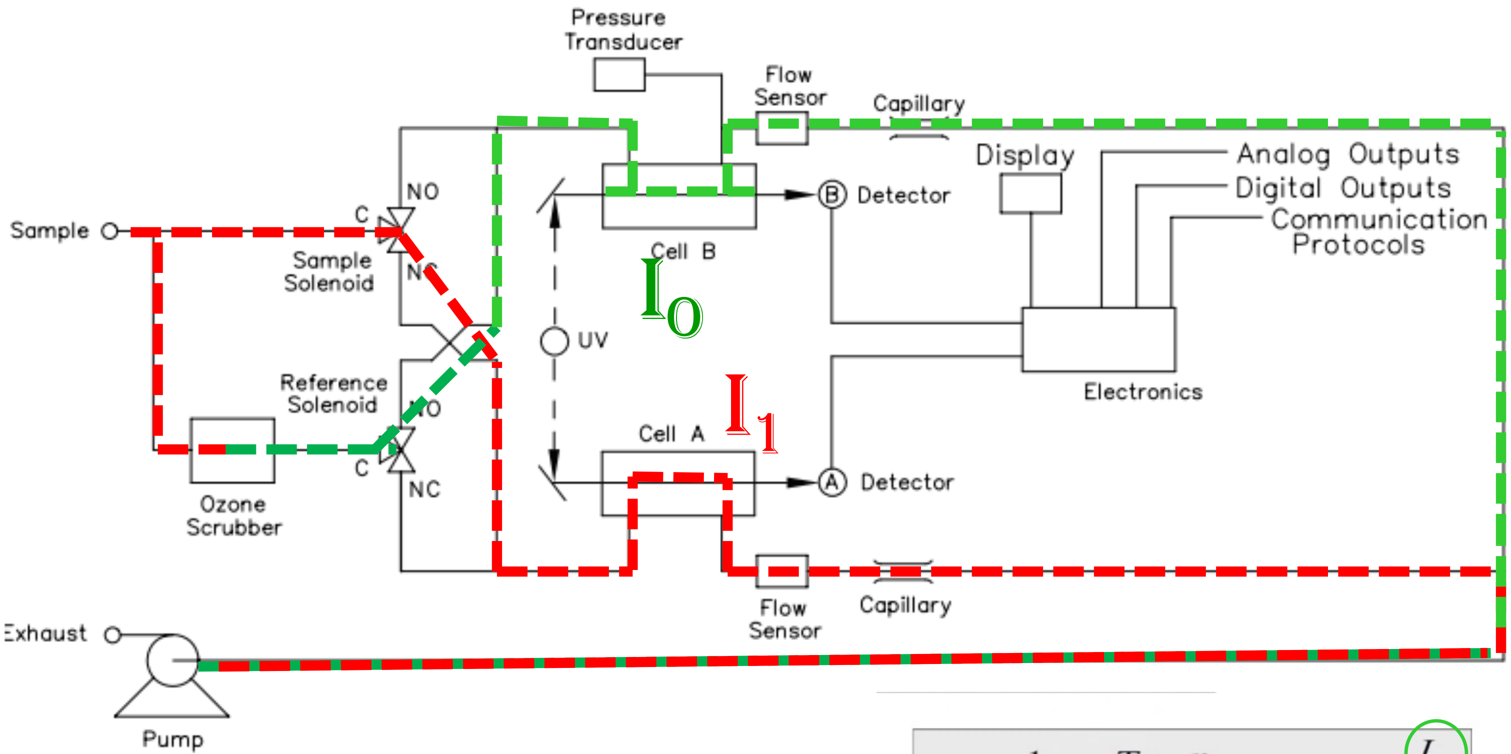


High T -> stability and integrity issues



Lamp intensity -> check cells, to regulate intensities

In-situ ozone measurement techniques



$$C = \frac{1}{k \cdot L} \cdot \frac{T}{T_0} \cdot \frac{p_0}{p} \cdot 10^9 \cdot \log \frac{I_0}{I_1}$$

Figure 1-1. Model 49*i* Flow Schematic

In-situ ozone measurement techniques

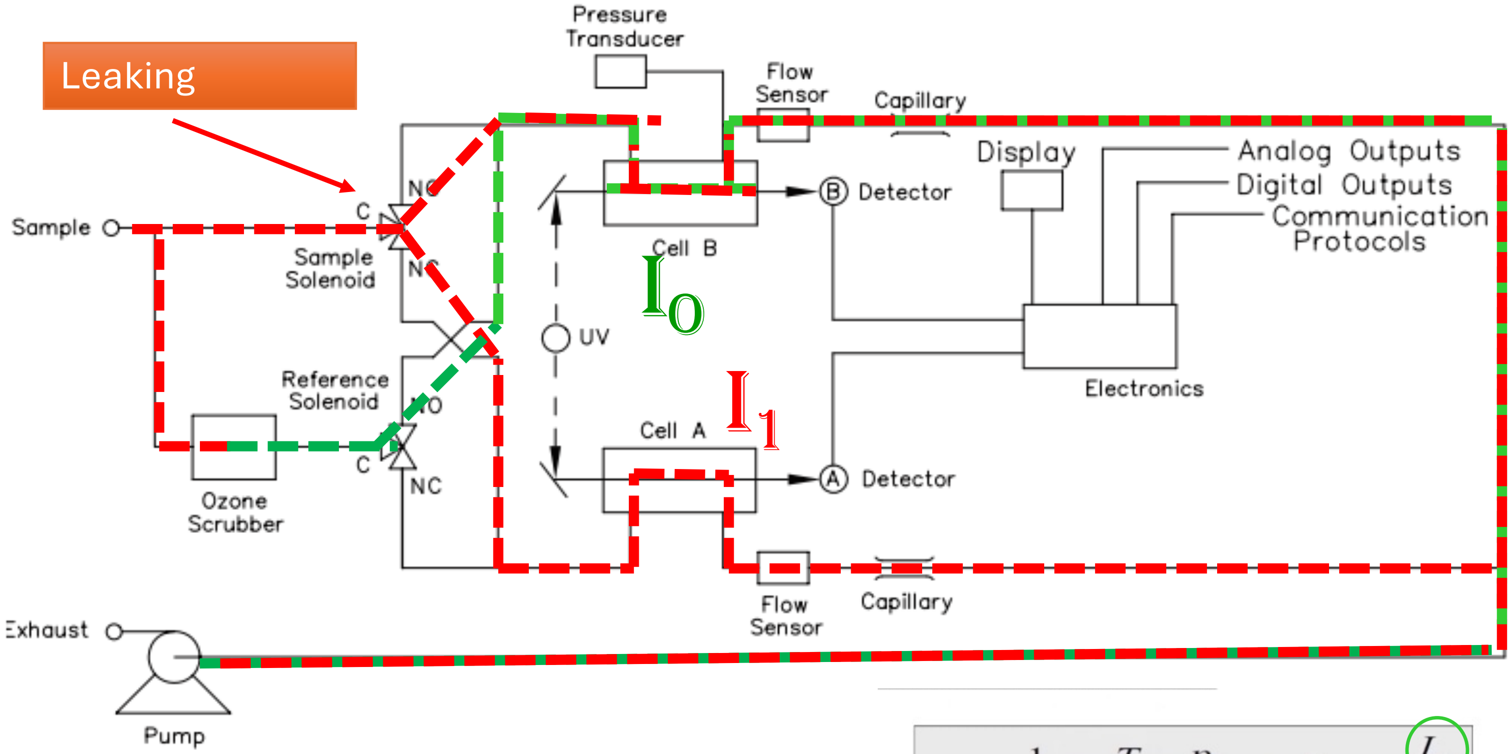


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Figure 1-1. Model 49*i* Flow Schematic

In-situ ozone measurement techniques

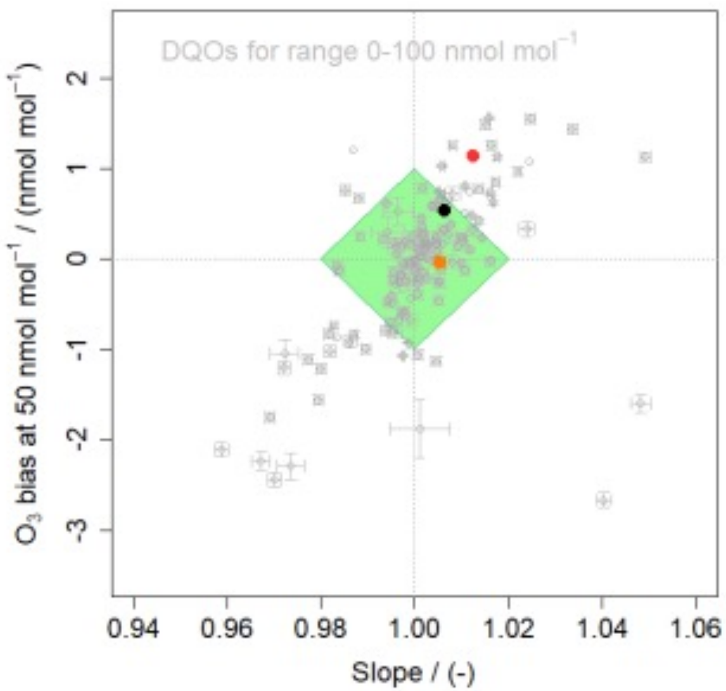
- If a calibrator or an ozone generator is available, leaks trough solenoids can be detected by using the «balance» cell A/B test
- At 500 ppb ozone, 10 consecutive readings of cell A and B should not deviate more than 3%
- If the case -> exchange cells to determine if the problem is related to one (dirty) cell.
- Then make a solenid leak test (follow manual)

	#	A	B
	1	488	510
	2	500	499
	3	490	509
	4	500	500
	5	489	511
	6	511	489
	7	496	504
	8	501	498
	9	480	518
	10	510	491
AVG		496.5	502.9
Difference		1.3 %	

	#	A	B
	1	464	510
	2	475	499
	3	466	509
	4	475	500
	5	465	511
	6	485	489
	7	471	504
	8	476	498
	9	456	518
	10	485	491
AVG		471.7	502.9
Difference		6.6 %	

Data quality objectives (GAW Report No. 209)

- To **detect tropospheric ozone trend,** the combined measurement uncertainty must be approximately ± 1 nmol mol^{-1} or less
- For **model assimilation and validation**, a combined uncertainty of less than ± 5 nmol mol^{-1} is required



O_3 bias in the middle of the relevant amount fraction range compared to the slope of the WCC-Empa performance audits.

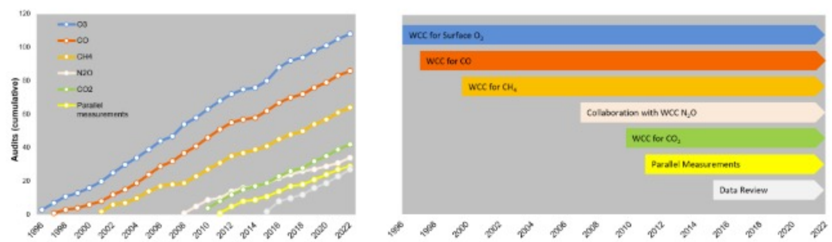
The coloured areas correspond to the WMO/GAW compatibility goals (green) and the extended compatibility goals (yellow).

Suggested citation. Zellweger, C., Steinbacher, M., and Emmenegger, L.: System and Performance Audit of Surface Ozone, Carbon Monoxide,Methane and Carbon Dioxide at the Global GAW Monte Cimone, Italy, September 2023, WCC-Empa Report 23/3, Dübendorf, Switzerland, 2024.

WCC-Empa Report 23/3

World Calibration Centre (WCC-Empa) for Surface Ozone, Carbon Monoxide, Methane, Carbon Dioxide and Nitrous Oxide

WCC-Empa was established in 1996, assuming worldwide responsibility for surface ozone, carbon monoxide and methane comparisons at global GAW stations. WCC-Empa was also mandated to extend its activities to carbon dioxide in 2010 and nitrous oxide in 2025.



Cumulative number (left) and scope (right) of WCC-Empa audits since 1996

In-situ ozone measurement techniques

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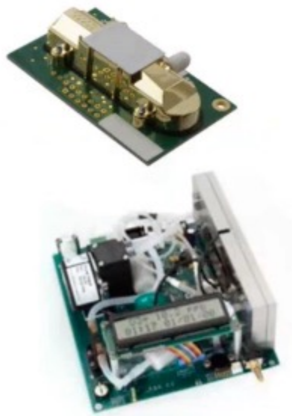
Instrument development: Low-end

Zellweger C., "measurement of tropospheric ozone", GAWTEC Webinar Series. https://www.youtube.com/watch?v=_DksbpztnQU

Metal oxide
~ CHF 5
~ 1960

Electrochemical
/ voltammetric
~ CHF 50
~ 1980

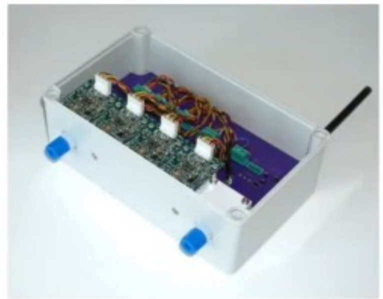
Photochemical
~ CHF 200
~ 1990



Model 106-L-OEM Ozone Monitor

Micro-optical
> CHF 100
~ 2000

decentLab



Trend:

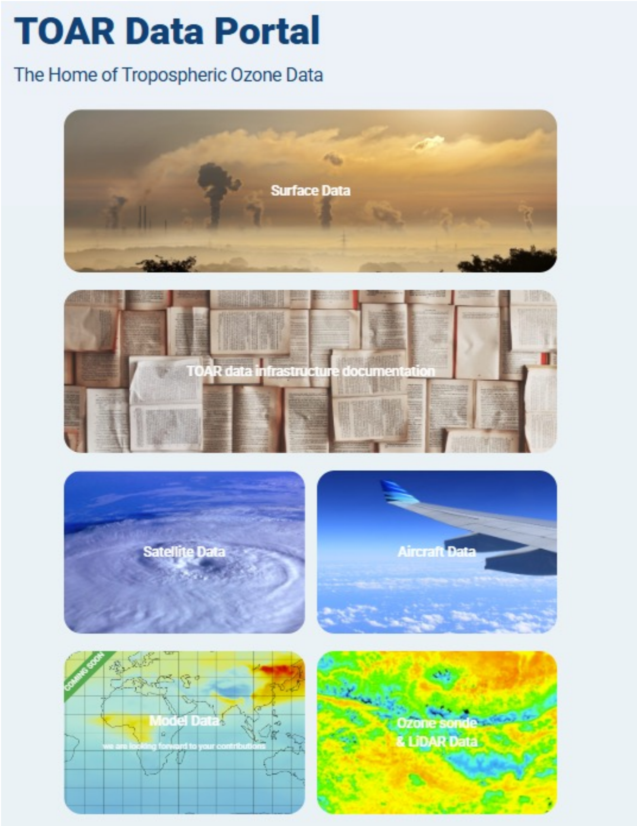
- Miniaturization
- Design improvements
- Integration into units
- Ancillary parameters (e.g. p, T)
- Multiple sensors
- Communication (LoRa / GSM)
- Cloud processing

Sensor → Micro-electro-mechanical (MEMS) type device

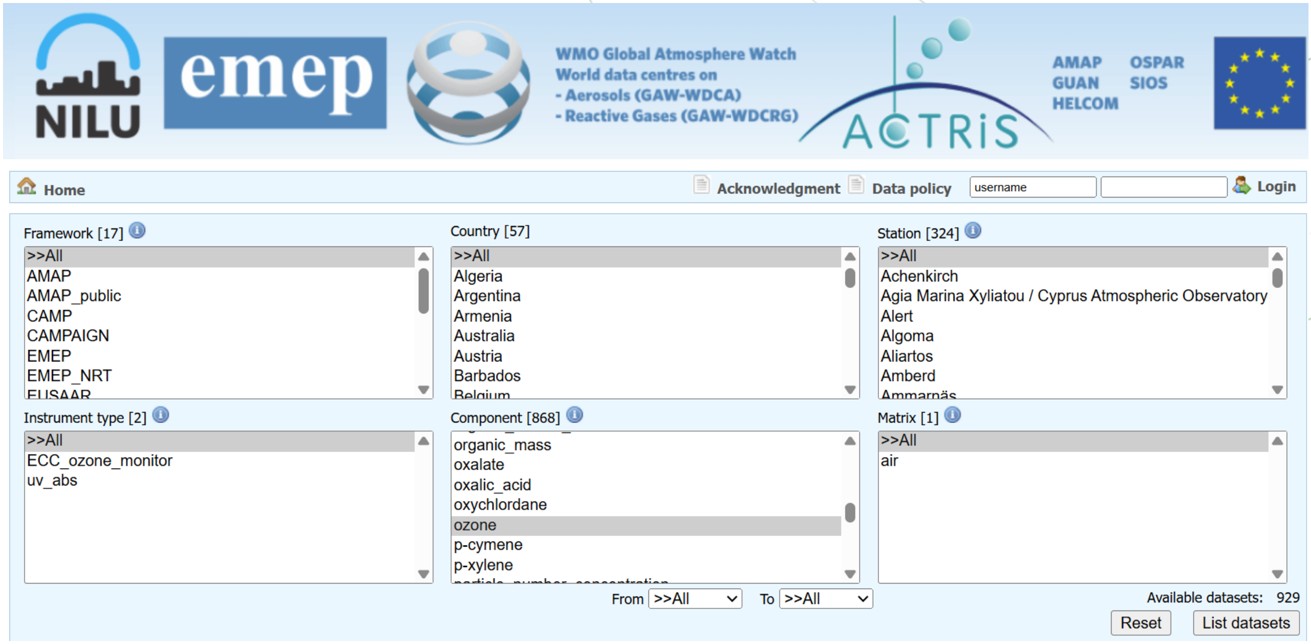
- Sensors: Challenging component diversity. Mainly 'old' technologies.

Tropospheric ozone (data repositories)

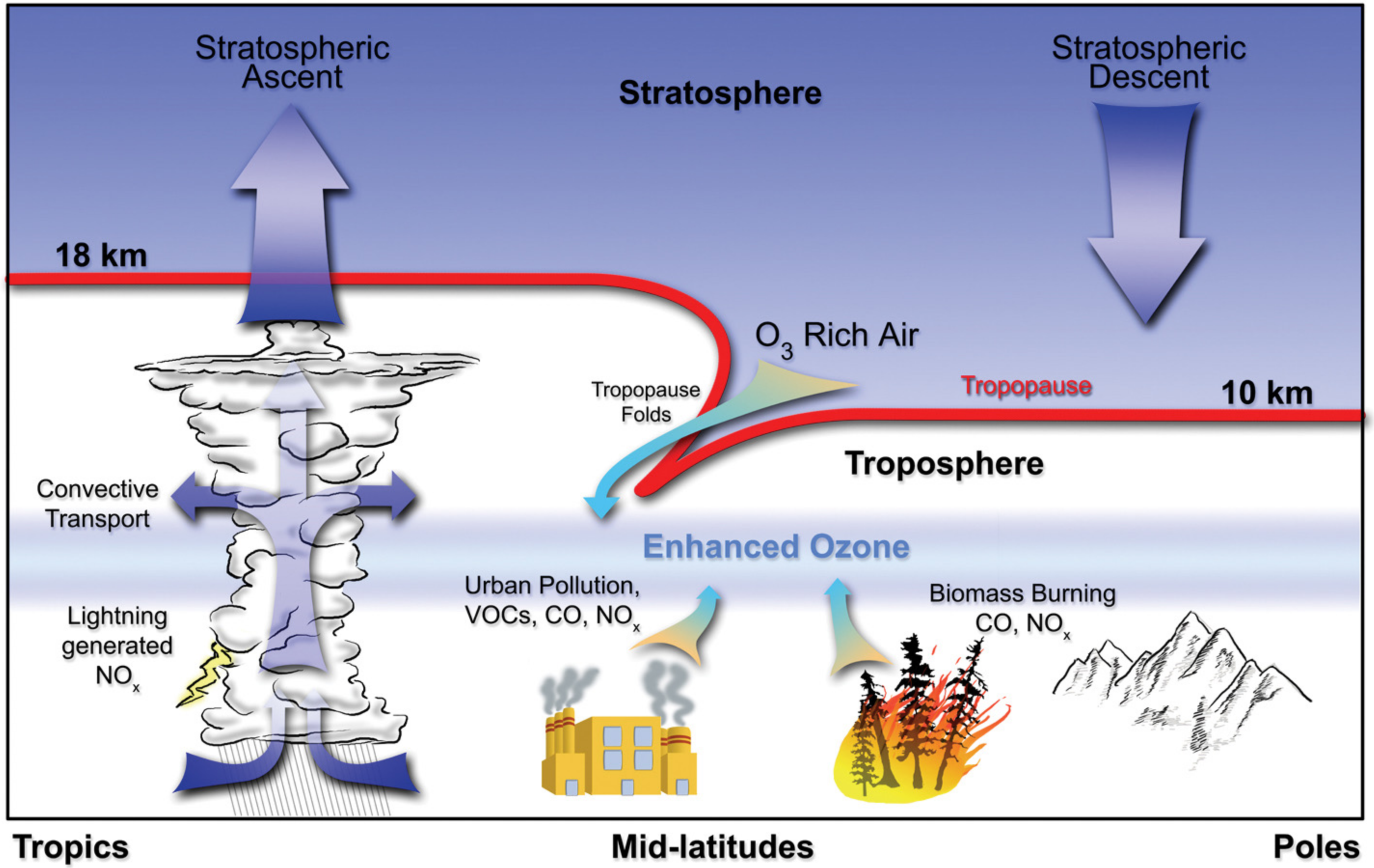
https://toar-data.org/surface-data/



https://ebas-data.nilu.no/



Tropospheric ozone (invstigation of processess)

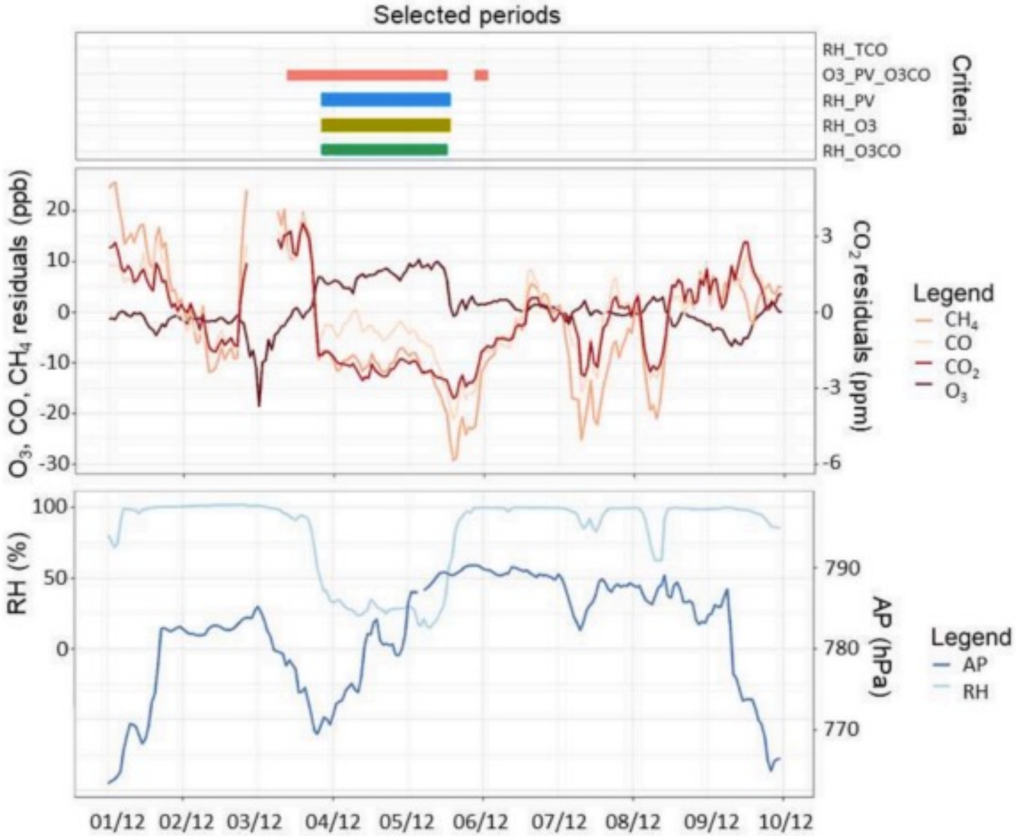


Tropospheric ozone: deep stratospheric intrusions

Influence of deep stratosphere-to-troposphere transport on atmospheric carbon dioxide and methane at the Mt. Cimone WMO/GAW global station (2165 m a.s.l., Italy): A multi-year (2015–2022) investigation

Pamela Trisolino [a], Davide Putero [b,*], Jgor Arduini [c], Stefano Amendola [d], Francescopiero Calzolari [a], Paolo Cristofanelli [a]

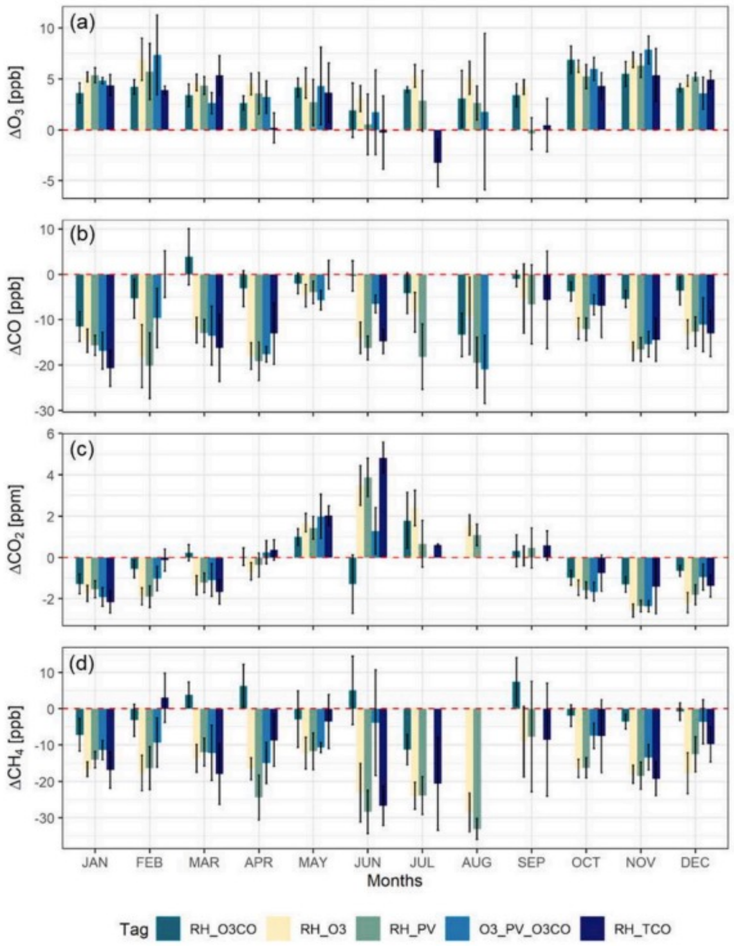
https://doi.org/10.1016/j.atmosres.2024.107627



Criteria for selecting STT events

1. RH 6-h running mean lower than 40% and significant O_3 increase (denoted as "RH_O3")
2. RH 6-h running mean lower than 40% and negative O_3 vs CO correlation ("RH_O3CO")
3. significant O_3 increase with at least one back-trajectory/day with PV $\geq$ 2.0 pvu and negative O_3–CO correlation ("O3_PV_O3CO")
4. RH 6-h running mean lower than 40% and significant TCO increase ("RH_TCO")
5. RH 6-h running mean lower than 40% and at least one back-trajectory/day with PV $\geq$ 2.0 pvu ("RH_PV")

Tropospheric ozone: deep stratospheric intrusions



Influence of deep stratosphere-to-troposphere transport on atmospheric carbon dioxide and methane at the Mt. Cimone WMO/GAW global station (2165 m a.s.l., Italy): A multi-year (2015–2022) investigation

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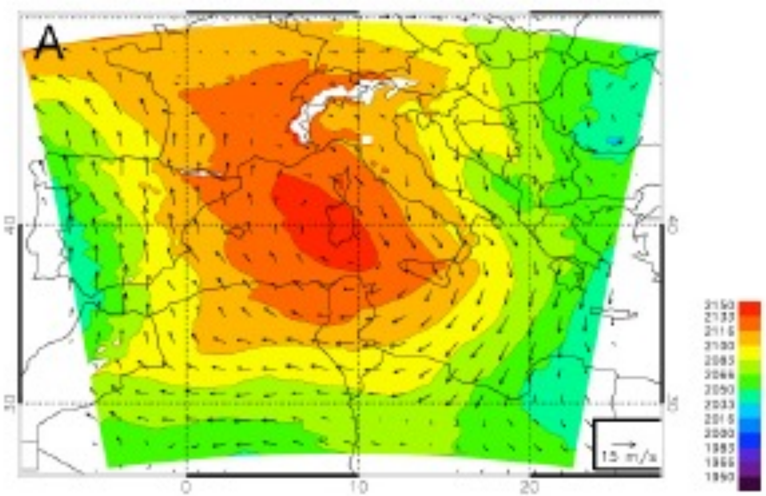
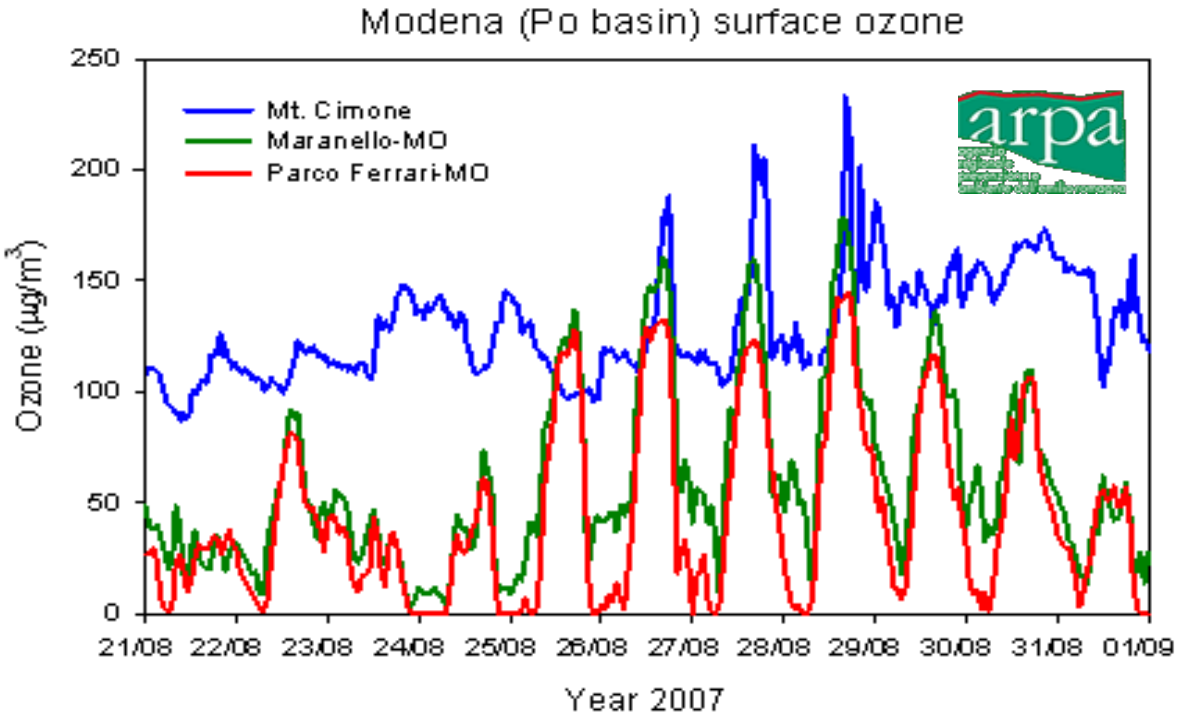
https://doi.org/10.1016/j.atmosres.2024.107627

- Data identified as affected by STT showed higher residuals for O_3.
- With respect to the remaining data, STT-affected periods showed a 4.2 ± 1.7 ppb (mean ± 1 σ) increase in O_3.
- O_3 increase maximised in DJF and minimised in JJA.
- Clear impacts also on CO, CO_2 and CH_4

Tropospheric ozone: transport of polluted air mass

Geopotential height (expressed in meters, coloured scale)
and wind vectors at 800 hPa, deduced by BOLAM analysis on 26
August 2007 12:00 UTC **(A)**
29 August 2007 12:00 UTC **(B)**.



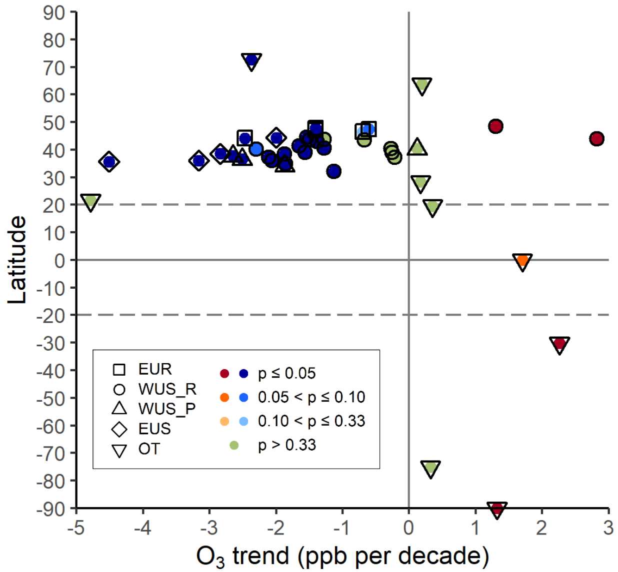


Atmos. Chem. Phys., 9, 4603–4619, 2009
www.atmos-chem-phys.net/9/4603/2009/

Atmospheric Chemistry and Physics

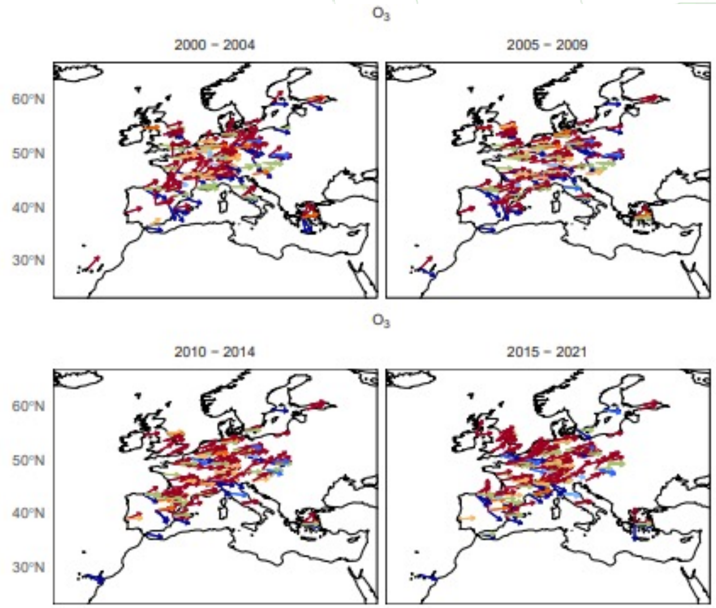
Trospospheric ozone: a look to long-term trends

High-elevation O_3 trends (41 sites)

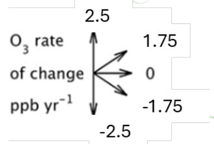


- 41 high-elevation (700 – 3900 m a.s.l.) sites
- Trends calculated on monthly anomalies
- >50 % on hourly data availability for each month
- quantile regression on the 50th quantile
- Generally decreasing trends in the middle northern latitudes

Putero et al. (2023). https://doi.org/10.5194/acp-23-15693-2023



Urban O_3 trends (144 sites) – 50th quantile



- 144 urban European sites
- Trends calculated on monthly anomalies
- >90 % on hourly data availability for each month
- Piecewise quantile regression on 0.5 – 0.95 quantiles (to identify breakpoints)
- Slowing in the increase of high European O_3, more site with upward trend in 2015-2021 than 2000 – 2004.
- Majority of trends positive and of high certainty ($p <= 0.05$) in Europe across the 20-year period.

Bates et al. (2025). https://doi.org/10.5194/egusphere-2024-3743

Trospospheric ozone (references)

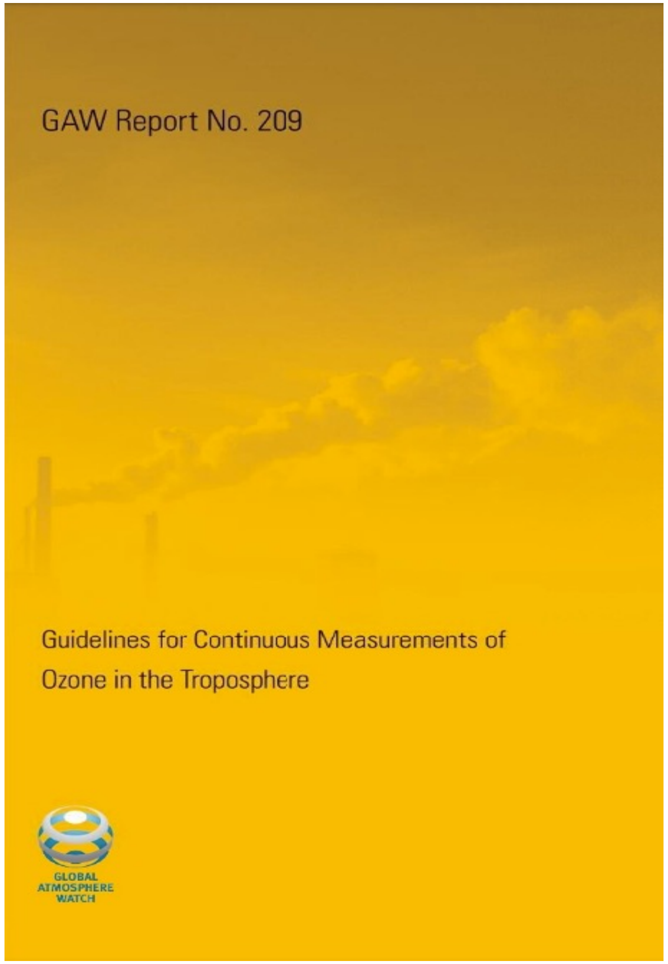


TABLE OF CONTENTS

https://library.wmo.int/viewer/49557/?offset=#page=1&viewer=picture&o=bookmarks&n=0&q=

Trospospheric ozone (references)

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arXiv > stat > arXiv:2304.14236

Search... Help

Statistics > Applications

[Submitted on 27 Apr 2023]

Guidance note on best statistical practices for TOAR analyses

Kai-Lan Chang, Martin G. Schultz, Gerbrand Koren, Niklas Selke

The aim of this guidance note is to provide recommendations on best statistical practices and to ensure consistent communication of statistical analysis and associated uncertainty across TOAR publications. The scope includes approaches for reporting trends, a discussion of strengths and weaknesses of commonly used techniques, and calibrated language for the communication of uncertainty. The focus of this guidance note is placed on trend analysis, which is expected to be the main statistical topic of interest across many TOAR-II focus working groups, but some of the recommendations and principles provided below are also valid for other applications. Recommendations are highlighted and numbered from R1 to R9.

Subjects: **Applications (stat.AP)**; Methodology (stat.ME)
Cite as: arXiv:2304.14236 **[stat.AP]**
(or arXiv:2304.14236v1 **[stat.AP]** for this version)
https://doi.org/10.48550/arXiv.2304.14236

Submission history

From: Kai-Lan Chang [view email]
[v1] Thu, 27 Apr 2023 14:54:31 UTC (11,273 KB)

Table 1: A brief comparison of statistical capabilities of three commonly applied techniques.

	GLS	Sen-Theil	**Quantile regression[1]**
Inference statistics of a trend	Mean	Median	**Percentile/Quantile**
Robust to small sample size		✔	*[2]
Robust to outliers		✔	✔
Makes use of all available information	✔		✔
Inference with non-normal distribution on residuals		✔	✔
Unique solution	✔		
Adjustment for non-IID residuals (e.g. Incorporation of autocorrelation)	✔		✔
Incorporation of covariates	✔		✔
Extend to piecewise trends	✔		✔
Extend to adaptive nonlinear trends	*[3]		*[3]
Extend to extreme percentile estimate			✔[2]

[1] Least absolute deviations method (median regression) can be considered to be a special case of quantile regression, so it is not listed independently.

[2] For quantile regression, the median estimate is robust to the small sample size problem, but a larger sample size is required for extreme percentile estimates (depending on applications, Das et al., 2019). See Table 2 for TOAR-specific recommendations.

[3] These extensions can be made via the class of standard or quantile generalized additive models.

TOAR
tropospheric ozone assessment report

Guidance note on best statistical practices for TOAR analyses

Kai-Lan Chang[1], Martin G. Schultz[2], Gerbrand Koren[3], and Niklas Selke[2]

[1]Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder and NOAA Chemical Sciences Laboratory, Boulder, CO, USA
[2]Jülich Supercomputing Centre, Forschungszentrum Jülich, Germany
[3]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, the Netherlands

This document has been produced based on discussions in the statistics focus working group of the TOAR-II initiative, and approved by the TOAR-II Steering Committee
April 26, 2023

The aim of this guidance note is to provide recommendations on best statistical practices and to ensure consistent communication of statistical analysis and associated uncertainty across TOAR publications. The scope includes approaches for reporting trends, a discussion of strengths and weaknesses of commonly used techniques, and calibrated language for the communication of uncertainty. The focus of this guidance note is placed on trend analysis, which is expected to be the main statistical topic of interest across many TOAR-II focus working groups, but some of the recommendations and principles provided below are also valid for other applications. Recommendations are highlighted and numbered from R1 to R9.

1 Definition of trend analysis

The purpose of trend analysis can be defined as

```
detecting and attributing the change and its uncertainty of the
statistical properties in a time series of a predefined variable.
```

where the statistical properties represent how we define and express the trend (e.g. mean, median or extreme percentile changes). Each component of this definition will be discussed through relevant topics and recommendations as follows: Section 2 clarifies the distinct roles of linear and nonlinear techniques in trend quantification. Section 3 compares the commonly adopted statistical properties in trend assessment. Section 4 discusses data preparation for time series analysis. Section 5 identifies the fundamental factors affecting uncertainty quantification associated with the trend estimate. Section 6 demonstrates how the reliability of trend assessment can be determined through the relationship between quantified trend and uncertainty. Section 7 discusses the change point detection of trends. Section 8 provides additional resources.

This guidance note aims to provide recommendations of tropospheric ozone trend analysis from a practical aspect, without discussing technical details, although we do provide some R and Python code for quantile regression in the Annex E. Practitioners (referring to authors of publications written in the context of the TOAR activity) who are interested in the fundamental theory of trend analysis (e.g. the statistical relationship between the sample size, magnitude of trend and uncertainty) are referred to various textbooks (Chandler and Scott, 2011; Von Storch and Zwiers, 2001; Wilks, 2011) and articles (Chang et al., 2021; Weatherhead et al., 1998).

2 Quantitative versus qualitative summary of the trend

R1: Practitioners are recommended to provide quantitative trends and should avoid drawing conclusions when the magnitude of trends and associated uncertainties are not explicitly quantified.

Trend detection techniques can be generally classified as linear or nonlinear methods. By using a large number of parameters and numerical optimization, nonlinear methods offer a great deal of flexibility in modeling the nonlinear pattern of a time series. However, the result is often too complex mathematically to quantitatively provide a simple trend value and an uncertainty value. Unless there is a clear understanding of (non-linear) processes driving the trend, quantitative non-linear trend analysis poses the risk of overfitting.

1

Trospospheric ozone (references)

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Atmospheric Measurement Techniques

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Tropospheric Ozone Assessment Report Phase II (TOAR-II) Community Special Issue (ACP/AMT/BG/GMD inter-journal SI)

Editor(s): AMT co-editors: Steffen Beirle, Diego Loyola, and Troy Thornberry | Co-organizers: Owen R. Cooper and Martin G. Schultz
Special issue jointly organized between Atmospheric Chemistry and Physics, Atmospheric Measurement Techniques, Biogeosciences, and Geoscientific Model Development

> The Tropospheric Ozone Assessment Report (TOAR-II) is an official activity of the International Global Atmospheric Chemistry Project (IGAC) (https://igacproject.org/activities/TOAR/TOAR-II). The goal of TOAR-II is to build on the success of TOAR-I (2014–2019) and produce an updated assessment of tropospheric ozone's global distribution and trends from the surface to the tropopause. This effort includes an analysis of the impacts of ozone on human health, crop and ecosystem productivity, and climate.

Trospospheric ozone (references)

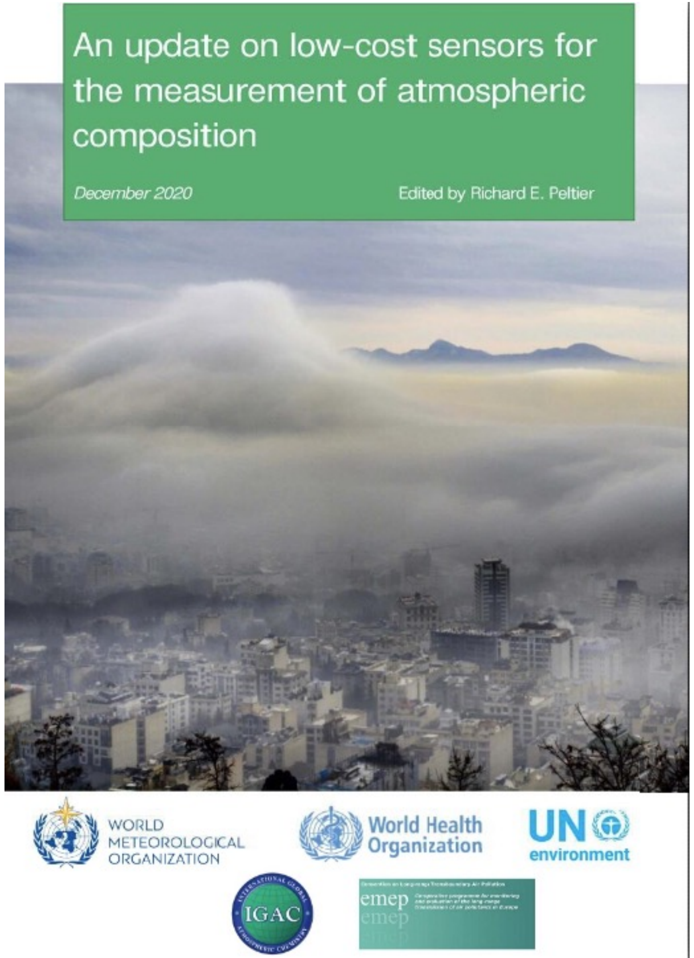

Table of Contents

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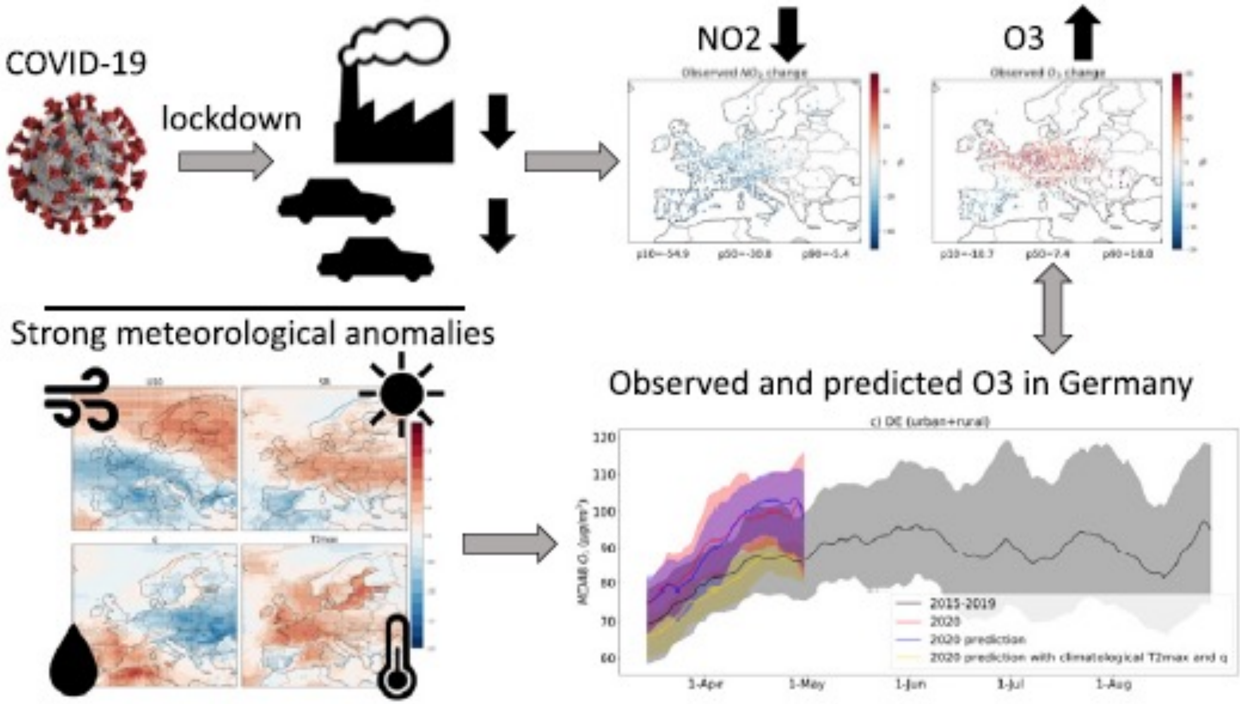
IR0000032 – ITINERIS, Italian Integrated Environmental Research Infr
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Genera
Mission 4 “Education and Research” - Component 2: “From research to bu ... estment
3.1: “Fund for the realisation of an integrated system of research and innova... infrastructures”

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani

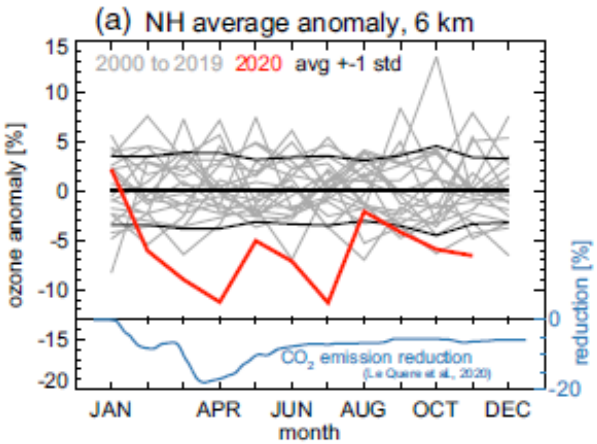
Fingerprints of the COVID-19 economic downturn



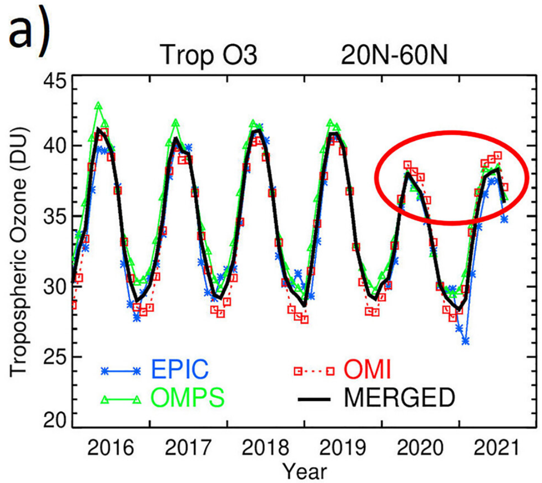
- ❑ At the begin, most of these works focused on high-emission sources or urban environments
- ❑ Varying O_3 behavior as a function of the reduction in the emissions, mainly dependent on whether the photochemical O_3 formation in the considered regions was NOx- or VOC-limited

Ordóñez C. et al., 2020 Early spring near-surface ozone in Europe during the COVID-19 shutdown: Meteorological effects outweigh emission changes *Sci. Total Environ.* **747** 141322. https://doi.org/10.1016/j.scitotenv.2020.141322

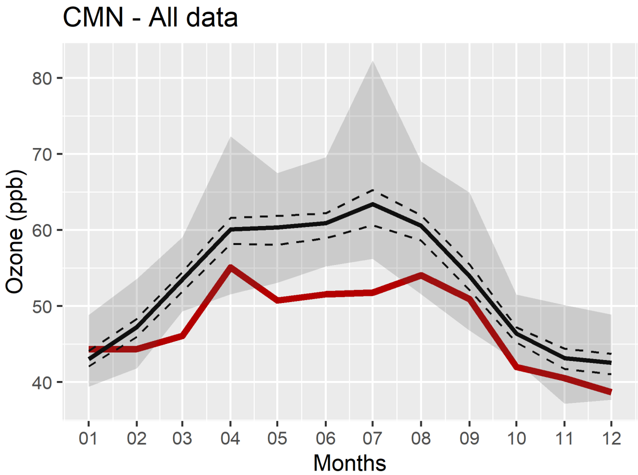
Fingerprints of the COVID-19 economic downturn



Steinbrecht, et al. (2021). https://doi.org/10.1029/2020GL091987



Ziemke et al. (2022). https://doi.org/10.1029/2022GL098712

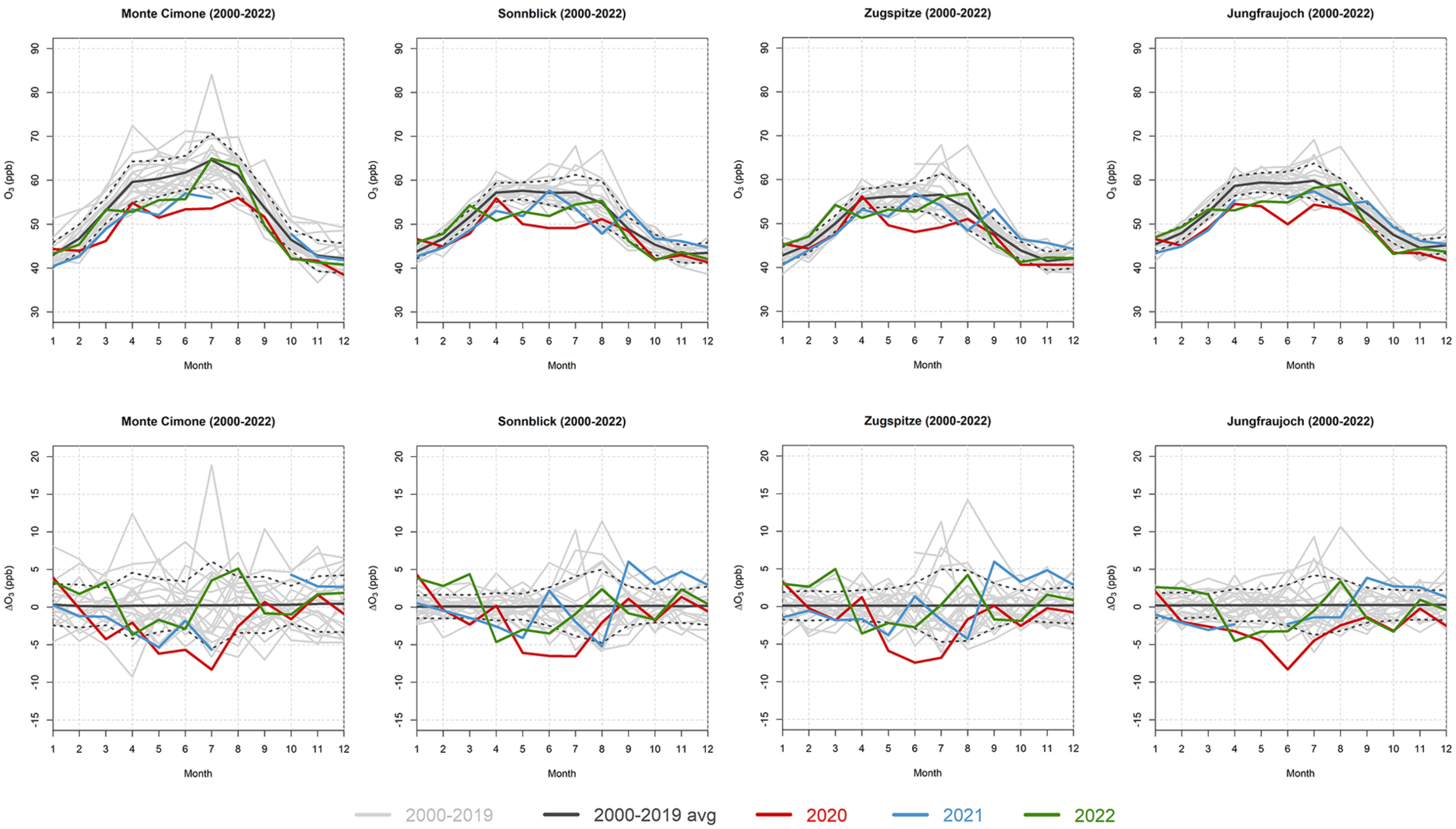


Free-troposphere: consistent reduction of O_3 in 2020-2021 as seen, e.g., by

- ground-based remote sensing (Steinbrecht et al., 2021)
- in-situ mountain top observations (Cristofanelli et al., 2021)
- satellite measurements of tropospheric column O_3 (Ziemke et al., 2022)

Cristofanelli et al. (2021). https://doi.org/10.1088/1748-9326/ac0b6a

Fingerprints of the COVID-19 economic downturn



https://doi.org/10.5194/acp-23-15693-2023

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Fingerprints of the COVID-19 economic downturn

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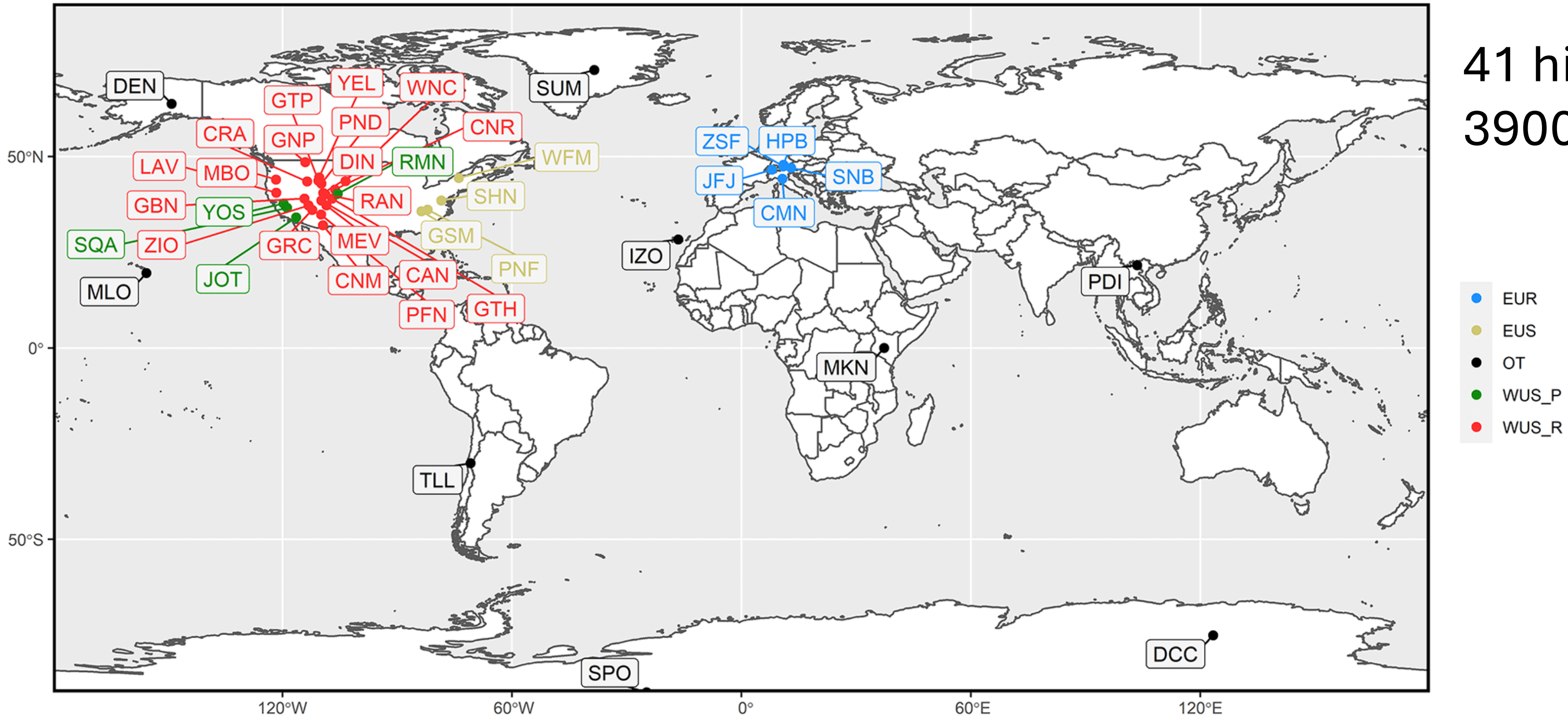

41 high-elevation (700 – 3900 m a.s.l.) sites

Season	WUS_R	WUS_P	EUS	EUR	OT
MAM 2020	−3.1 ppb (−6 %)	−4.3 ppb (−9 %)	−2.5 ppb (−4 %)	−2.1 ppb (−3 %)	−2.1 ppb (−3 %)
JJA 2020	−2.3 ppb (−5 %)	−2.9 ppb (−4 %)	−5.6 ppb (−12 %)	−4.8 ppb (−8 %)	−1.5 ppb (−5 %)
MAM 2021	−0.9 ppb (−2 %)	0.4 ppb (3 %)	0.9 ppb (3 %)	−2.7 ppb (−4 %)	−1.3 ppb (−1 %)
JJA 2021	2.7 ppb (6 %)	1.2 ppb (3 %)	−3.8 ppb (−8 %)	−2.6 ppb (−5 %)	0.4 ppb (1 %)

https://doi.org/10.5194/acp-23-15693-2023

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