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Recent changes in the O_3 and CO trends in the troposphere as observed by IAGOS

Thibaut Lebourgeois[1*], Valérie Thouret[1], Hannah Clark[2], Yasmine Bennouna[1], Romain Blot[1], Damien Boulanger[3], Florian Brunet[1], Simon Cleris[1], Jean-Marc Cousin[1], Philippe Nedelec[1], Julie Patuel[1], Pawel Wolff[3**], and Bastien Sauvage[1]

[1]Laboratoire d'Aérologie, Université de Toulouse, CNRS, IRD, Toulouse, France
[2]IAGOS-AISBL, 98 Rue du Trône, Brussels, Belgium
[3]Observatoire Midi-Pyrénées, Université de Toulouse, CNRS, IRD, 31400 Toulouse, France
[*]Now at Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany
[**]Now at European Centre for Medium-Range Weather Forecasts (ECMWF) Bonn, Germany.

Correspondence: Thibaut Lebourgeois (thibaut.lebourgeois@dlr.de)

Abstract.

IAGOS has been measuring Ozone (O_3) and Carbon Monoxide (CO) since 1994 and 2002 respectively. This dataset allows us to calculate O_3 and CO trends in the upper troposphere across nine regions of the Northern Hemisphere. Trends are computed over multiple time periods to highlight recent changes.

O_3 growth in the upper troposphere (UT) of the Northern Hemisphere was more pronounced between 1994 and 2013 (e.g 0.34 ± 0.09 ppbv/yr in East US and 0.32 ± 0.07 ppbv/yr in Europe). These trends are significantly higher than those calculated from 1994 to 2023 (0.17 ± 0.07 ppbv/yr in East US and 0.16 ± 0.05 ppbv/yr in Europe). This difference in trend of O_3 appears to be associated with high positive anomalies of O_3 in the early 2010s, as well as significantly lower O_3 levels after 2020, at least partially linked to the COVID-19 crisis.

For CO, we observe a gradual reduction in its rate of decline over the years, until a point where trends are no longer detected or are associated with low positive values since the 2010s at mid-latitudes in the Northern Hemisphere.

Further studies will be necessary to constrain the causes of recent O_3 and CO variations. Continued IAGOS monitoring over the coming years will be essential, to further update this analysis and to determine whether the recent change in the observed trends are temporary or represent a sustained change in the upper tropospheric air composition.

1 Introduction

CO is a critical component for understanding atmospheric composition. It acts as a precursor to both O_3 and carbon dioxide (CO_2) (Seinfeld and Pandis, 2016) while also serving as a major sink for hydroxyl radicals (OH), thereby indirectly extending the atmospheric lifetime of other greenhouse gases and pollutants (Lelieveld et al., 2016). For these reasons, CO is recognized as a gas with an indirect positive radiative effect (Szopa et al., 2021). Additionally, CO is frequently used as a tracer for combustion processes and surface pollution (e.g., Lebourgeois et al. (2024)). Analyzing its trends can thus provide valuable insights into the evolution of global emissions.

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O_3 plays a central role in atmospheric chemistry as one of the dominant oxidant in the troposphere, significantly affecting air quality and human health (Crutzen et al., 1999). It is also a potent greenhouse gas, contributing to radiative forcing and global climate change (Szopa et al., 2021). Understanding the long-term evolution of O_3 across the atmosphere is therefore critical for both environmental policy and climate projections (Fleming et al., 2018; Mills et al., 2018).

Since the discovery of the Antarctic O_3 hole forty years ago (Farman et al., 1985) and the implementation of the Montreal Protocol adopted in 1987 following the Vienna Convention for the Protection of the stratospheric O_3 Layer, trends have been extensively monitored. While signs of recovery have emerged following the reduction of O_3-depleting substances, the response is not uniform throughout the stratosphere (Laine et al., 2014). Recent studies report positive trends in the upper stratosphere but continued negative trends in the lower stratosphere, indicating a slower-than-expected overall recovery (Ball et al., 2018). Furthermore, this heterogeneous behavior can be masked when considering only total column O_3 due to compensating increases in the troposphere (Ball et al., 2018).

In the troposphere, O_3 concentrations have also evolved over recent decades in response to shifts in precursor emissions from anthropogenic and natural sources (Cooper et al., 2014; Gaudel et al., 2024). Numerous analyses have documented increasing O_3 trends in many regions of the world, particularly in the Northern Hemisphere (e.g. Cooper et al. (2014); Cohen et al. (2018); Gaudel et al. (2024); Boynard et al. (2025); Thompson et al. (2025); Van Malderen et al. (2025)). These increases are linked to changes in atmospheric composition and photochemistry driven by nitrogen oxides (NO_2), volatile organic compounds, and CO. Although CO emissions have generally decreased, tropospheric O_3 production remains more sensitive to NO_x and VOC precursors than to CO (Elshorbany et al., 2024).

Recent events like the COVID-19 pandemic can also impact the trend of several gases. During the pandemic, changes in human activity led to strong perturbations in precursor emissions, resulting in a change in O_3 values during that period (Clark et al., 2021; Gkatzelis et al., 2021).

Recent observations and synthesis reports like the Tropospheric Ozone Assessment Report (TOAR) further indicate a shift in O_3 trend patterns, with the strongest positive trends now emerging in the tropics and regions with intense emissions or major biomass burning events (e.g.,Gaudel et al. (2024); Thompson et al. (2025)). However, significant discrepancies remain between instruments and retrieval techniques. For instance, UV-based remote sensing datasets predominantly show positive tropospheric trends, whereas IASI satellite measurements often report negative trends due to their enhanced sensitivity to lower-tropospheric O_3 (Boynard et al., 2025). These inconsistencies underline the importance of cross-validation using independent datasets such as O_3 sondes and IAGOS aircraft observations, which frequently highlight disagreements with remote sensing products.

Nevertheless, large uncertainties persist, particularly in recent years, owing to limited observational coverage in some regions and differences in measurement sensitivity across datasets. Given the complexity of O_3 chemistry and the variability of regional trends, accurately assessing the long-term evolution of tropospheric O_3 remains a research priority. There are few datasets available for such studies.

IAGOS (Thouret et al. (2022), https://www.iagos.org) has provided O_3 measurements since August 1994 along flight tracks from the ground to the cruise altitude, at global scale given the participating airlines operating routes. Among other scientific interests and usages, IAGOS is considered a key data set for analysing trends of tropospheric O_3 (and lower stratosphere). First

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estimate of interannual variability of O_3 were given by Thouret et al. (2006), followed by a first 20-year analysis by Cohen et al. (2018). This paper will present the most recent analysis of the IAGOS data set for O_3 and CO along with the methodology which has been used to assess the trends. Section 3 will present and discuss the results in terms of regional difference and in terms of vertical variabilities. Section 4 gives a final discussion and prospects to further analyse and understand the leading processes.

2 Data set and methodology

2.1 IAGOS

The European research infrastructure In-service Aircraft for a Global Observing System (IAGOS), formerly known as the Measurement of O_3 and Water Vapor by Airbus In Service Aircraft (MOZAIC), has collected continuous high-quality O_3 and CO profiles up to 12 km ($\sim$200 hPa) on board commercial aircraft since 1994 for O_3 and 2002 for CO. O_3 is measured using an ultraviolet (UV) analyzer (Thermo Scientific, model 49) and the total uncertainty is respectively $\pm$ 2 nmol.mol^{-1} $\pm$ 2% and $\pm$ 5 nmol.mol^{-1} $\pm$ 5% for O_3 and CO respectively (Nédélec et al., 2015).

2.1.1 Region and altitude layers

For this study, we consider 9 regions (Fig. 1), as defined in Cohen et al. (2018) that represent the most sampled regions by the equipped aircraft over the 20-30 year period. North-East Asia in Cohen et al. (2018) have been modified because of the change in operations in this part of the world (see section 2.1.3 below, on Data Quality). The regions Tropical Africa and South Asia have also been added to the regions already studied by Cohen et al. (2018). The number of IAGOS flights per region and defined periods is showed in table A1.

In this study, the Upper Troposphere (UT) is defined as follows: Altitude > 8000m and Potential Vorticity (PV) < 2.

2.1.2 Airport clusters

IAGOS O_3 measurements are acquired both during aircraft cruise phases, sampling the upper troposphere and lower stratosphere (UTLS), and during take-off and landing phases, which provide vertical profiles of the lower and middle troposphere near major airports. Therefore, each flight delivers two atmospheric profiles, one during ascent and one during descent, enabling high-frequency vertical sampling in regions with dense air traffic. To derive robust O_3 trends from these profile data, airports are grouped into clusters. These airport clusters must be sufficiently sampled to ensure meaningful temporal coverage. Here we retain only airport clusters with a return interval of no more than a few weeks on average to ensure robust trend computation.

The city airport included in the airport clusters are described below:

- Eastern US: New York (US), Boston (US), Philadelphia (US), Washington (US), Newark (US), Detroit (US), Cincinnati (US), Montreal (CA), Chicago (US).

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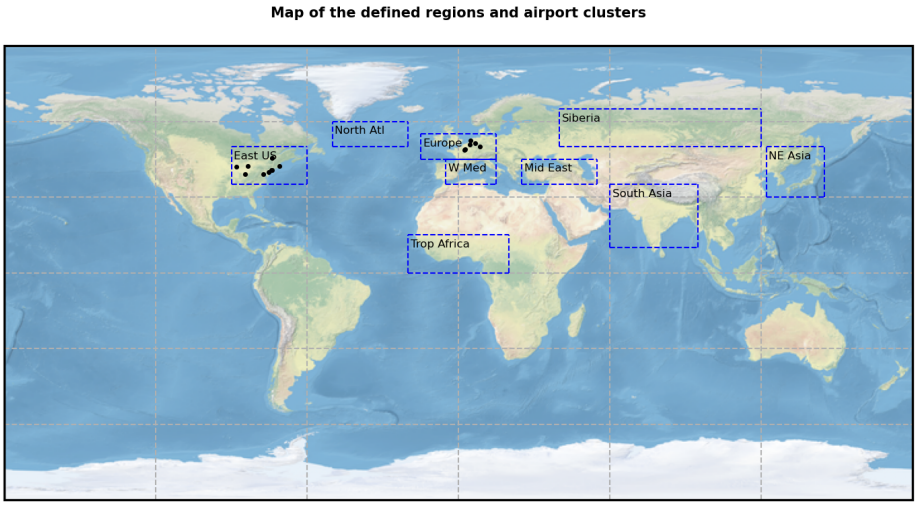

Figure 1. Map of the defined regions and positions of the studied airports

– Europe: Frankfurt (Germany),Brussels (Belgium), Düsseldorf (Germany), Amsterdam (Netherland), Paris (CDG and Orly) (France).

2.1.3 Data quality

Trend analysis requires stability in both measurement instruments and model-derived parameters. A comprehensive internal consistency analysis study has already demonstrated that measurements from IAGOS and its predecessor, MOZAIC, are sufficiently consistent to be treated as a single, unified dataset (Blot et al., 2021). In addition, it is worth mentioning that the IAGOS instruments intercompare very well with the reference instrument (the dual-beam UV-Ozone (O_3 PhotoMeter) of the World Calibration Center of O_3 Sondes. This has been tested and documented in Smit et al. (2025), thus ensuring the robustness of the IAGOS data set for harmonized trends calculations.

Since the start of IAGOS measurements, the number of cruising pressure levels has evolved, with an increase in the diversity of flight altitudes over time and aircraft flying on average higher during the last decade. IAGOS measurement started in 1994 with only Airbus A340. Since 2013 IAGOS has equipped Airbus A330 that fly at higher altitude on average than its predecessor. To address this, we carefully verified that these changes in flight levels did not introduce artifacts in the measured CO or O_3. Therefore, additional sensitivity tests were conducted to ensure that no major changes in flight altitudes or flight trajectories across the studied regions could introduce significant biases in the long-term trends of CO and O_3 mixing ratios. It is important to acknowledge minor variations related to the evolution of equipped aircraft fleets, airline policies, and safety regulations.

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Fig. A2 (in the appendix) illustrates the distribution of pressure levels before and after 2011. This figure reveals that the differences remain minimal, with a couple of new cruising pressure levels above 210 hPa. Trends calculated over a thinner upper tropospheric layer (220 to 350 hPa), equally sampled over the entire period (and excluding the new flight levels), have been calculated and showed no significant differences with the normal layer (Fig A1 in the appendix). Consequently, it is unlikely that these minor variations in flight levels would introduce any significant bias in our observed trends.

Regional sampling biases may also arise due to changes in the deployment of equipped aircraft within regional airlines. For instance, the reallocation of long-haul aircraft to domestic routes can alter the spatial coverage of measurements. This reason explains the modification of the East Asian region studied in Cohen et al. (2018) and the smaller one defined here and centered around a zone equally sampled during the entire period. Additionally, geopolitical events at the global scale have further impacted the regional sampling by IAGOS aircraft. Prior to 2021, flight trajectories frequently included routes over Siberia. However, following the Russian invasion of Ukraine, most airlines have avoided Russian airspace, resulting in the loss of sampling coverage for this region. It hence must be kept in mind that the Siberian region ceased to be sampled after 2021. Furthermore, the COVID-19 pandemic and its associated lockdowns and border closures significantly disrupted global air traffic, thereby affecting IAGOS measurements. As a result, 2020 was poorly sampled across most regions, and the limited data available for this year have been excluded from the present analysis.

All these factors, including changes in aircraft deployment, geopolitical constraints, and pandemic-related disruptions, have been systematically verified. This analysis confirms that none of these changes introduced significant biases in the trends analysis of CO or O_3.

2.2 Quantile regression

Quantile regression (QR) is a statistical method that allows the estimation of trends at different quantiles of a variable's distribution, providing a more comprehensive view of its evolution over time (Koenker and Hallock, 2001). This approach offers several advantages for trend analysis: it is robust to outliers, captures heterogeneous changes across the distribution, and can be applied directly to non-aggregated datasets with irregular sampling intervals and missing values. QR has been recommended by the Tropospheric Ozone Assessment Report (TOAR) for O_3 trend analysis and is described in detail in Chang et al. (2023). Since O_3 and CO time series often exhibit strong autocorrelation, 95% confidence intervals for QR trends are estimated using a moving block bootstrap procedure, as described in Chang et al. (2023).

In this study, the QR method was applied to deseasonalized (see section below) IAGOS measurements across different geographic regions and altitude layers, enabling a detailed assessment of trends throughout the troposphere and lower stratosphere. The robustness of the trends will be assessed using p-values and, more importantly, the Signal-to-Noise Ratio (SNR) defined as the trend values divided by the uncertainty (Chang et al., 2023). TOAR recommendations are to use SNR thresholds to communicate uncertainty:

- 2 <= SNR < 3 high certainty
- 1.65 <= SNR < 2 medium certainty

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- 1 <= SNR < 1.65 low certainty
- SNR < 1 no evidence

2.3 Data preparation

Quantile regression was used to estimate O_3 trends. One major advantage of this method is that it does not require monthly aggregation, as it is robust to extreme values and irregular temporal sampling. This makes it particularly well suited for IAGOS measurements, which exhibit variable sampling frequency.

Data were only aggregated into daily averages to facilitate data processing.

A comparison between trends derived from monthly-aggregated data and from data kept at their native temporal resolution has been reported by Van Malderen et al. (2025) and they found only minor differences between the two approaches.

To remove the influence of seasonal variability on O_3, the monthly mean climatology was calculated and subtracted from each measurement before trend analysis. Monthly means were only calculated when sufficient sampling was available, defined as observations distributed over more than three distinct days within a given month and separated by at least seven days. This criterion used in Cohen et al. (2018) avoids introducing biases in the seasonal cycle caused by months with sparse or temporally clustered data, ensuring a more reliable deseasonalization of the IAGOS time series.

3 Results

3.1 Upper Troposphere (UT)

In their study, Cohen et al. (2018) analyzed the trends of O_3 observed by IAGOS over the period 1994–2013. Here, we extend this analysis by incorporating data from subsequent years, up to 2023, to update these trends with the most recently validated data. This allows a comparative assessment of the 1994–2013 and 1994–2023 periods. The method described above has been applied to compute trends with the complete period (1994-2023) and to the period 1994-2013 studied by Cohen et al. (2018). It is important to note, however, that our method differs from the one used by Cohen et al. (2018), which could explain some of the differences with their results.

As illustrated in Figs. 3 and 2, the trends calculated over the full 29-year dataset (1994–2023) are significantly weaker than those derived from the 1994–2013 period, both for CO and O_3. In most regions O_3 trends have approximately halved (e.g., in Europe, the most frequently sampled region, the O_3 trend goes from 0.32 ± 0.07 ppbv/yr to 0.16 ± 0.05 ppbv/yr, while the CO trends goes from -1.36 ± 0.21 ppbv/yr to -0.4 ± 0.1 ppbv/yr). This indicates that the CO mixing ratio in the upper troposphere has been declining at a slower rate in recent years, while O_3 levels have been increasing less rapidly than in previous decades. Several recent studies have similarly documented this slowdown in O_3 increase over the past years over northern hemisphere mid-latitudes (Van Malderen et al., 2025; Boynard et al., 2025).

Fig. 4 provides insight into O_3 variations over recent decades, by representing the monthly mean anomalies over the 29 years. Blue colors represent monthly means lower than the monthly average computed between 1994 and 2023, while red

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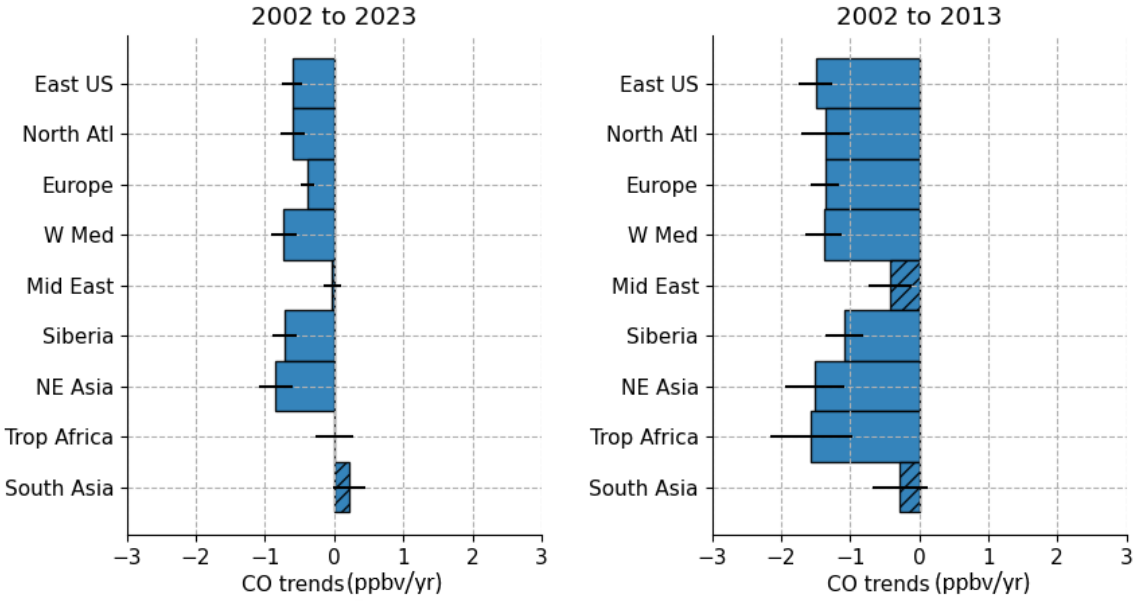

Figure 2. Upper Tropospheric trends of CO calculated from 2002 to 2023 (left) and from 2002 to 2013 (right) (in ppbv/yr). Hatched trends represent trends with low confidence (p value < 0.05 or SNR < 1.65).

colors represent monthly means higher than the average. All regions show higher mean mixing ratios in the 2010s compared to the mid-1990s. The changes observed between the 2010s and 2020 are less pronounced and appear to be seasonally dependent. In most regions, O_3 levels have either declined or remained stagnant. These patterns suggest a shift in O_3 trends over the past 15 years.

Table 1 presents the seasonal average values of O_3 and CO in the UT across the studied regions. The data reveal that the highest UT O_3 mixing ratio is observed in Siberia during JJA, reaching 92 ppbv. Similarly, the Middle East and Western Mediterranean regions exhibit elevated O_3 levels during MAM and JJA, with values approaching 80 ppbv. Conversely, Tropical Africa records the lowest averages, with O_3 mixing ratios around 50 ppbv across all seasons. For CO, the maximum values in the UT of the Northern Hemisphere typically occur during MAM. This seasonal peak is attributed to the wintertime accumulation of CO in the lower troposphere, followed by enhanced transport during spring, which significantly elevates CO mixing ratios in the UT (Zbinden et al., 2013; Petetin et al., 2016; Cohen et al., 2018).

Fig. 5 is similar to Fig. 4 but for CO. For CO the monthly averages are computed between 2002 and 2023. Here, it is clear that negative anomalies appear as early as the 2010s. It is also important to note strong seasonal (especially in summer) anomalies in the most recent years. This is due to the intense boreal wild fires that occurred in 2021, 2022 and mostly 2023 (Zheng et al., 2023; Byrne et al., 2024).

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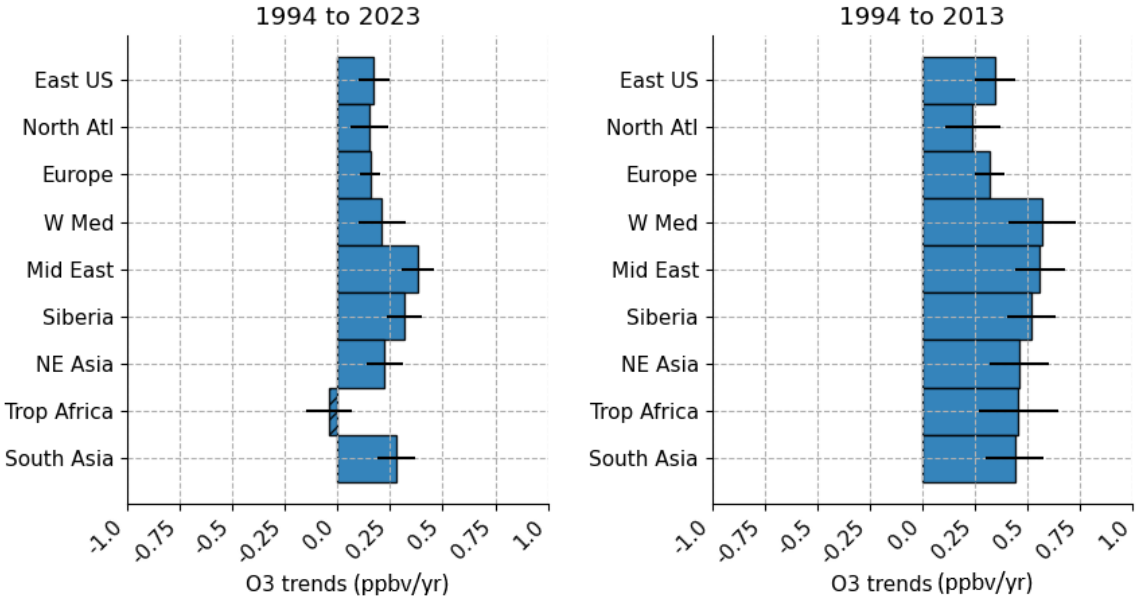

Figure 3. Upper Tropospheric trends of O_3 calculated from 1994 to 2023 (left) and from 1994 to 2013 (right) (in ppbv/yr). Hatched trends represent trends with low confidence (p value < 0.05 or SNR < 1.65).

Fig. 4 appears to highlight a change in O_3 anomalies, with negative anomalies transitioning to positive around the 2010s. Interestingly, a similar but inverted pattern is observed for CO in most of the studied regions (Fig. 5).

O_3 trends are typically weak (generally on the order of a few %/decade in the literature (e.g Thompson et al. (2025)), making it challenging to visually discern a trend from these figures alone. The methods recommended by the Tropospheric Ozone Assessment Report (TOAR) to highlight shifts in trends involve calculating trends over successive periods (Chang et al., 2023). Consequently, the following figure presents rolling trends computed over 10-year windows centered on each year.

Fig. 6 illustrates the running trend calculated for a ten years period for O_3 and CO in Europe. This analysis reveals a notable shift in the O_3 trend around the mid 2010s.

While the results are most robust in Europe (where data density is highest) similar patterns are observed in other regions, though the timing of the trend break may vary by a few years. Given the relatively short time frame over which these trends are calculated, this figure does not provide a robust quantitative assessment and a solid conclusion but provides an unambiguous qualitative estimate of the period during which the trend shift occurs. This period is around the years 2013-2015 ($\pm$ 5 years), revealing a parallel behaviour between O_3 and CO. It actually means that an O_3 maximum has been reached in the mid 2010s and O_3 levels have been decreasing since then (with medium to low certainty).

Fig. 6 shows a reversal in the sign of the trends occurring over the same period (centered around 2013, corresponding to the trend calculated over 2008–2018) for both CO and O_3.

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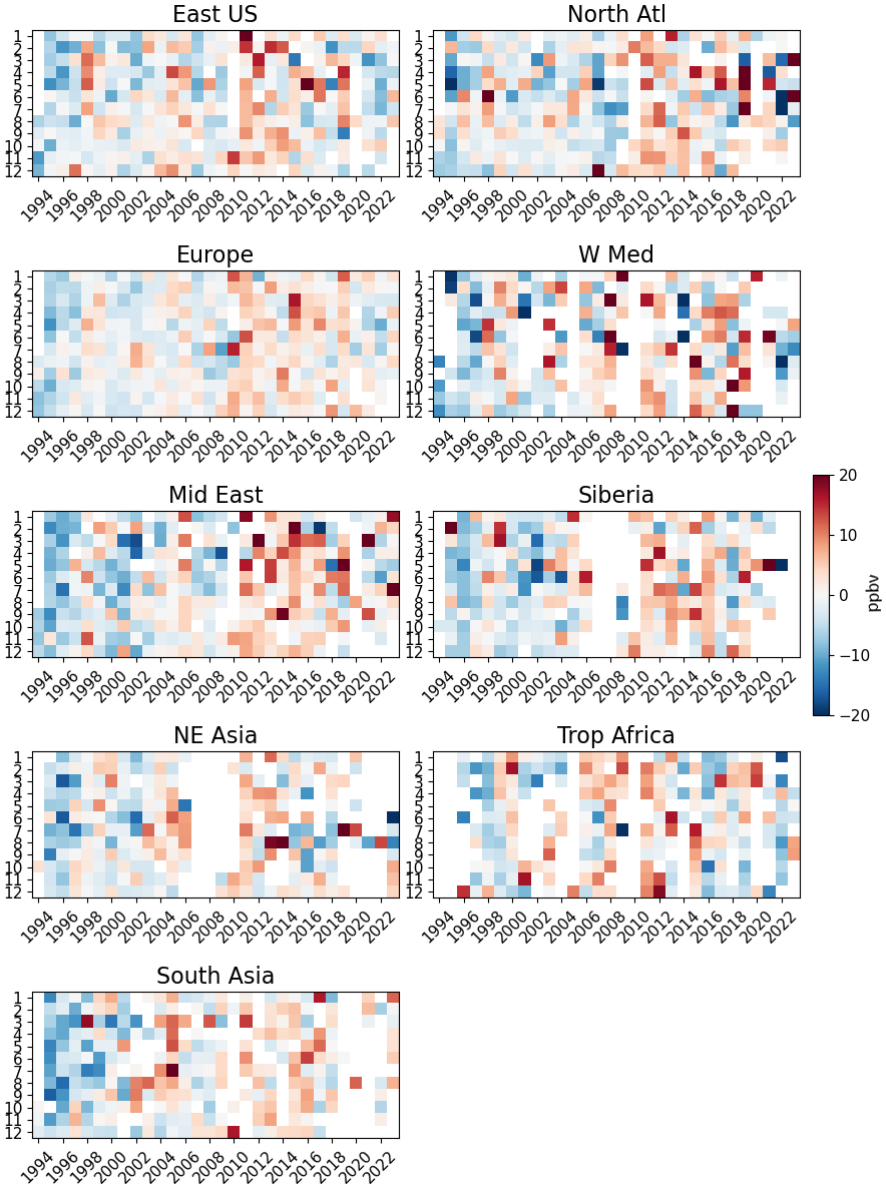

Figure 4. Upper tropospheric monthly O_3 anomalies (in ppbv). The x and y axis show the year and month of measurement respectively.

However, in contrast to O_3, the CO trend exhibits a continuous evolution, characterized by a progressively weakening negative trend that transitions to a positive trend in the mid-2010s. At the start of the IAGOS observations, CO was strongly decreasing with very high certainty, whereas since the mid 2010s CO started to increase in the UT with medium to low certainty. This trend is consistent with estimates and projections from various emission inventories, which indicate that reductions in anthropogenic CO emissions have become increasingly less effective in the US and Europe (Soulie et al., 2024). This suggests

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		DJF	MAM	JJA	SON
East US	CO	97	117	98	87
	O_3	52	75	79	54
North Atl	CO	97	111	97	86
	O_3	52	78	79	54
Europe	CO	99	111	95	87
	O_3	51	72	79	54
W Med	CO	93	108	84	82
	O_3	52	77	85	54
Siberia	CO	98	110	109	90
	O_3	54	79	92	58
Mid East	CO	90	103	86	79
	O_3	56	80	81	60
South Asia	CO	94	94	99	98
	O_3	52	66	63	53
NE Asia	CO	96	125	121	99
	O_3	57	77	74	58
Trop Africa	CO	123	130	110	109
	O_3	52	58	52	51

Table 1. CO and O_3 seasonal average values, as observed in the UT.

that anthropogenic CO emissions may have reached a plateau remaining nearly constant across most regions of the Northern Hemisphere.

205 However, anthropogenic CO emissions are not the unique factor influencing CO trends. Changes in VOC emissions, as well as an increase in CO emissions from wildfires, may also have a significant impact on these trends and could explain the positive trend due to positive anomalies observed in the later years of the study period because of intense boreal wildfires in the years 2022-2023 (Zheng et al., 2023; Byrne et al., 2024).

To refine our trend analysis for O_3, we define three distinct periods for calculation:

210 – The full period (1994–2023).

– The initial period (1994–2013), as used by Cohen et al. (2018).

– The recent period (2011–2023).

The latter period was deliberately chosen to start in 2011 (rather than 2014, as identified as the changing time from Fig. 6, right after 2010 which was a less sampled year) to ensure more than 10 years of complete measurements to compute the trend.

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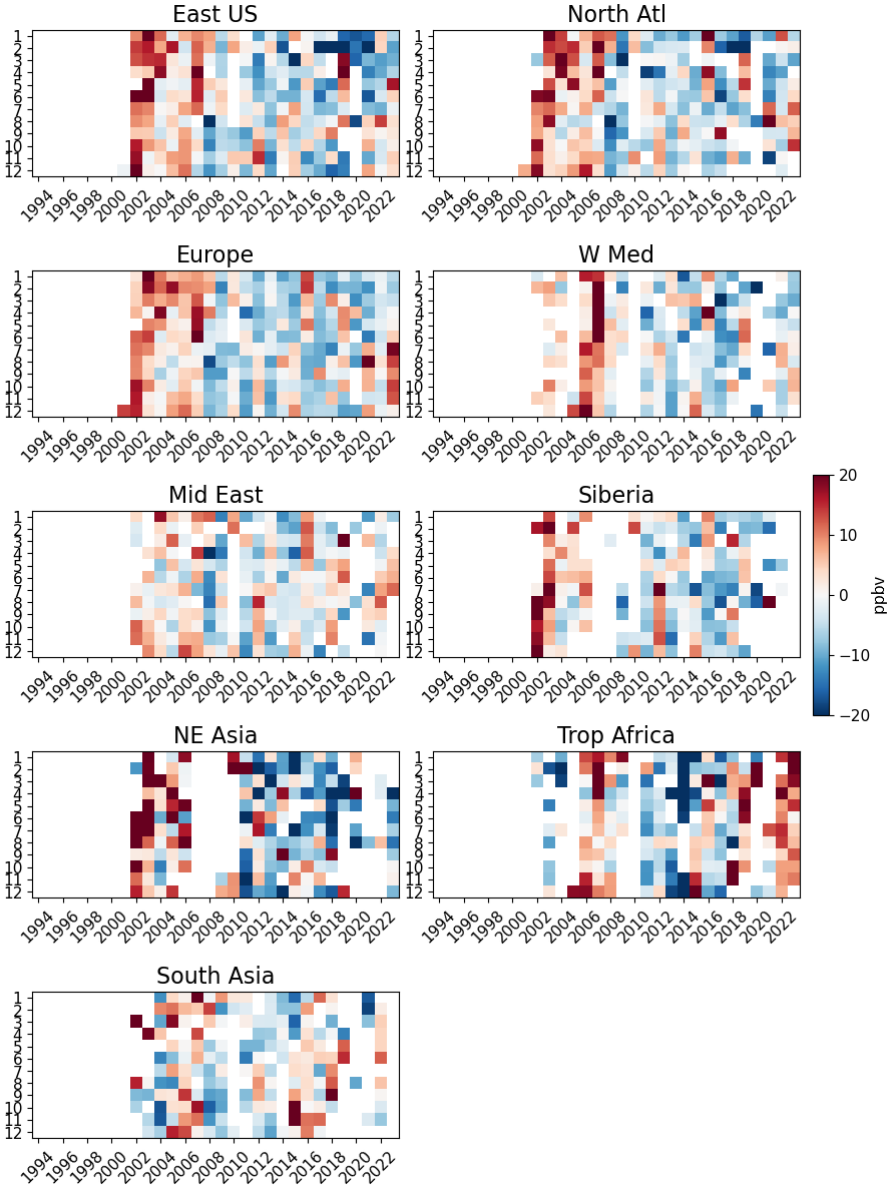

Figure 5. Upper tropospheric monthly CO anomalies (in ppbv). The x and y axis show the year and month of measurement respectively.

This decision accounts for the 2020 data gap, as the COVID-19 pandemic severely disrupted air traffic, resulting in almost no IAGOS observations for that year.

Figs. 7 and 8 present the calculated trends for O_3 and CO over the period 2011–2023.

Results from the previous section indicate that O_3 trends in the upper troposphere over the past 29 years are characterized by an increase in O_3 levels up to the early 2010s with high to very high certainty, partly reinforced by strong O_3 anomalies

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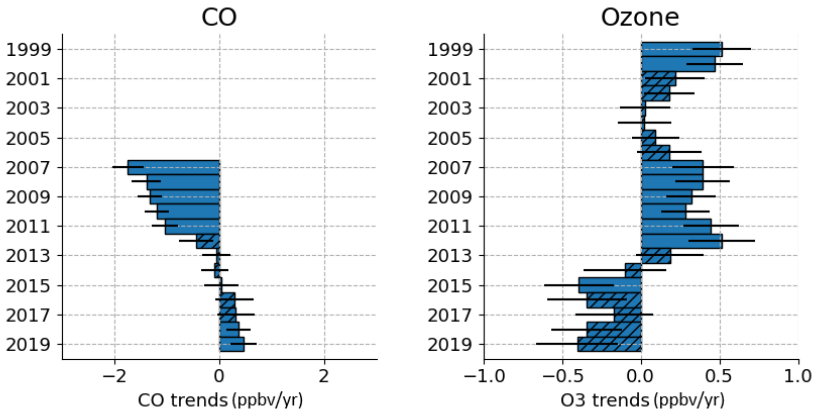

Figure 6. European moving trends (in ppbv/yr). A trend is calculated for a period of 10 years centred on each year. Hatched trends represent trends with low confidence (p value < 0.05 or SNR < 1.65).

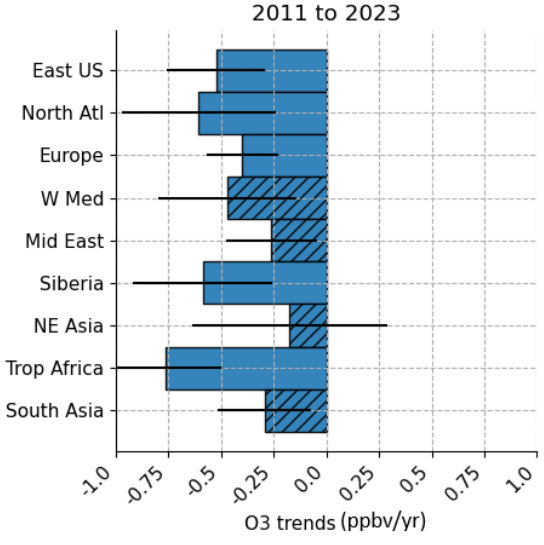

Figure 7. Upper Tropospheric trends of O_3 calculated from 2011 to 2023 (in ppbv/yr). Hatched trends represent trends with low confidence (p value < 0.05 or SNR < 1.65).

220 during this period (Cohen et al., 2018). This increase was followed by a slight decline in O_3 levels from the early 2010s to 2023 (with medium to high certainty depending on the region). As observed in the above figures, the O_3 trends presented here are negative and are associated with substantial uncertainty, as reflected by the large error bars. A couple of recent studies

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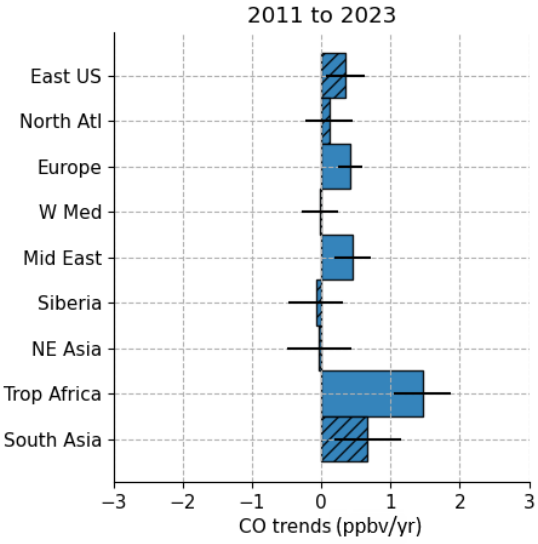

Figure 8. Upper Tropospheric trends of CO calculated from 2011 to 2023 (in ppbv/yr). Hatched trends represent trends with low confidence (p value < 0.05 or SNR < 1.65).

have demonstrated a decline in the absolute magnitude of O_3 trends at mid-latitudes in the Northern Hemisphere over the past decades (Boynard et al., 2025; Van Malderen et al., 2025).

Some of these studies attributed these changes, at least partially, to the COVID-19 pandemic (e.g Van Malderen et al. (2025)).

Sensitivity tests were conducted by recalculating trends up to 2019 (instead of 2023) to remove the influence of COVID-19-related disruptions. Due to the short time period, the calculated trends are associated with higher uncertainty. The trends (Fig. B1 in the appendix) show decreasing trends with low to no certainty (2011 to 2019). Trends calculated from 1994 to 2019 are associated with high to very high confidence and can be 50% higher than the trends calculated with full period (e.g trend values in Europe go from 0.16 ± 0.05 ppbv/yr to 0.24 ± 0.06 ppbv/yr for the period 1994/2023 and 1994/2019 respectively) and shows the impact of the COVID years over the calculated trends. The trends are calculated without the year 2020 (year with the most strict COVID-19 regulation) and could show the lasting impact of the COVID period over O_3 values. The year 2020 was anyway excluded from all our trend calculations due to the limited availability of data resulting from the COVID-19 pandemic and associated lockdown. It suggests that the COVID-19 crisis is not the unique factor driving the recent changes observed in O_3 trends over the past years.

Our results also indicate that the observed trends are heavily influenced by the peak in O_3 concentrations reached around the early 2010s. The most sensitive periods to trend variations are likely the anomalies observed in the early mid 2010s. These anomalies amplify the positive trend observed during the 1994–2013 period and reinforce the negative trend identified in the 2011–2023 period.

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According to Cohen et al. (2018), the O_3 anomaly observed during this period could be attributed to enhanced transport across the tropopause, modulated by ENSO phases. Indeed, O_3 concentrations and their variability in the upper troposphere are significantly influenced by stratosphere-troposphere exchange processes (Lin et al., 2015).

The positive trends and peak values observed in the early 2010s may also be attributed to a regime shift driven by variations in emissions of key O_3 precursors (NO_x, VOCs, CO) (Zeng et al., 2008; Archibald et al., 2020). Depending on the local chemical regime, trends in precursors and O_3 can either align or diverge, reflecting the influence of NO_x limited or VOC limited conditions on O_3 production (Elshorbany et al., 2024).

In a warmer climate, rising temperatures may also have a positive impact on O_3 levels, both by enhancing O_3 production and by increasing stratosphere-to-troposphere exchange (Zeng et al., 2008; Li et al., 2024). Additionally, higher temperatures promote biogenic VOC emissions, which can further influence O_3 concentrations (Zeng et al., 2008). Conversely, increased humidity in a warmer climate may, in contrast, have a negative effect on O_3 levels (Zeng et al., 2008; Belan and Savkin, 2019).

For CO, the previously observed decrease appears to have reached a plateau, with trends now exhibiting no trends or even positive values (in Europe with medium certainty) in the upper troposphere. It is critical to note that CO trends in the upper troposphere of each region are not solely indicative of local emissions but also reflect hemispheric-scale transport and secondary CO production. Anthropogenic CO emissions are still estimated to be decreasing in most regions of the Northern Hemisphere (Soulie et al., 2024).

The stagnation (or even increase in Europe) of CO values observed in the studied regions over the past 15 years could potentially be attributed to one of the following factors: increase of anthropogenic emissions, rising emissions of CO precursors, or an increase in wildfire-related emissions in recent years (Zheng et al., 2023; Byrne et al., 2024).

However, the slowdown in the decline of CO trends alone cannot account for the cessation of tropospheric O_3 increase observed over the past 15 years. CO is not the sole precursor of O_3 and, in fact, exerts a more limited influence compared with volatile organic compounds (VOCs) and NOx on O_3 formation (e.g Seinfeld and Pandis (2016)). Other precursors, such as NOx and VOCs, may also have contributed to the observed O_3 trends (Elshorbany et al., 2024).

It is important to bear in mind that these recent trends are calculated over a relatively short period of only 12 years (or even less for regions with limited data post-2020). Therefore, it would be premature to conclude that O_3 in the upper troposphere (UT) is now in decline. Instead, the data suggest that O_3 reached a peak in the early 2010s, followed by a phase of slight decrease in subsequent years that might be due to the covid-19 lockdown and continues until 2023.

Only the trend calculated since 1994 provides a sufficiently robust and long-term perspective to confidently assert that O_3 trends have been positive in most regions over this extended period and show an elevation of 0.16 ± 0.05 ppbv/yr (very high certainty) in Europe to a maximum of 0.38 ± 0.08 ppbv/yr (very high certainty) in the Middle East.

However, CO trends continue to exhibit a decline, ranging from -0.39 ± 0.10 ppbv/yr in Europe to -0.84 ± 0.24 ppbv/yr in NE Asia. This less pronounced decrease in CO levels, compared with previous estimates, is attributed to stagnation or even an increase (with medium certainty) of the trends of CO in certain regions, over the past decade.

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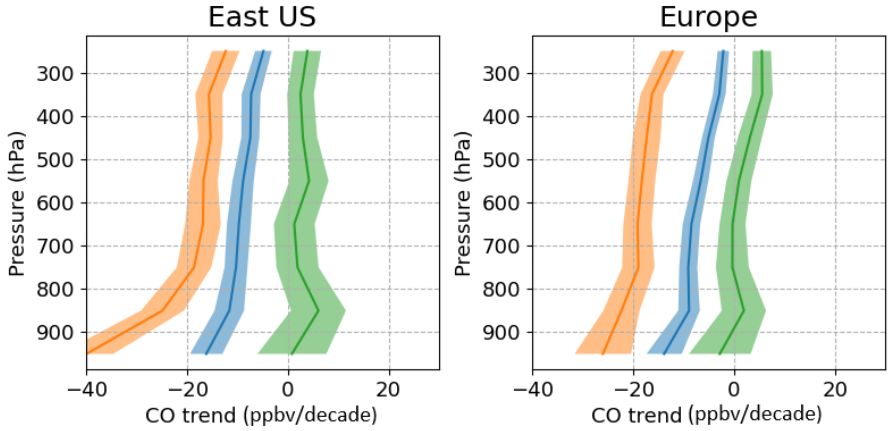

Figure 9. Profile of CO trends. Trends are calculated for three different periods: from 2002 to 2023 (blue), from 2002 to 2013 (orange) and from 2011 to 2023 (green) (in ppbv/yr).

3.2 Vertical profiles

Thanks to IAGOS measurements onboard passenger aircraft, trends can also be computed throughout the depth of the tropo-
275 sphere.

Trends in CO and O_3 concentrations are not only detected in the upper troposphere but are also observed at lower altitudes over Europe and the eastern United States and can be seen in Fig. 9 for CO and on Fig. 10 for O_3.

The primary characteristics of CO trends calculated in the upper troposphere (UT) are consistent with those observed throughout the rest of the troposphere. Overall, values of CO in these regions have shown a decline since the beginning of
280 IAGOS measurements in 2002 (blue curve for CO). In Eastern US, trends computed between 2002 to 2013 were more negative than the one computed in Europe in the lower troposphere, but reached similar values at higher altitude. Since the early 2010s, the trends have been close to zero or just slightly positive, with significant uncertainties, indicating that a floor may have been reached in the reduction of anthropogenic emissions from certain regions in the Northern Hemisphere (Soulie et al., 2024).

The O_3 trend profiles for the two regions are similar, with only minor differences observed primarily close to the surface.
285 Indeed, trend computed for Europe from 2011 to 2023 (green curve on Fig. 10) remained positive while in Eastern US those trends are associated with little to no certainty.

Since the beginning of measurements tropospheric O_3 values have increased by approximately 1 ppbv per decade. However, since 2011, the trends have been predominantly negative throughout the troposphere in the Eastern US with low to medium certainty and above 600 hPa in Europe with high certainty (green curve on Fig.10). These trends are associated with substantial
290 uncertainties, primarily due to sparser data availability and the shorter time period used for trend calculations.

The trend profile, characterized by more negative values at higher altitudes, may indicate an influence of stratosphere-to-troposphere exchange (STE) on the recent variations in O_3 trends. Recent studies have demonstrated that changes in strato-

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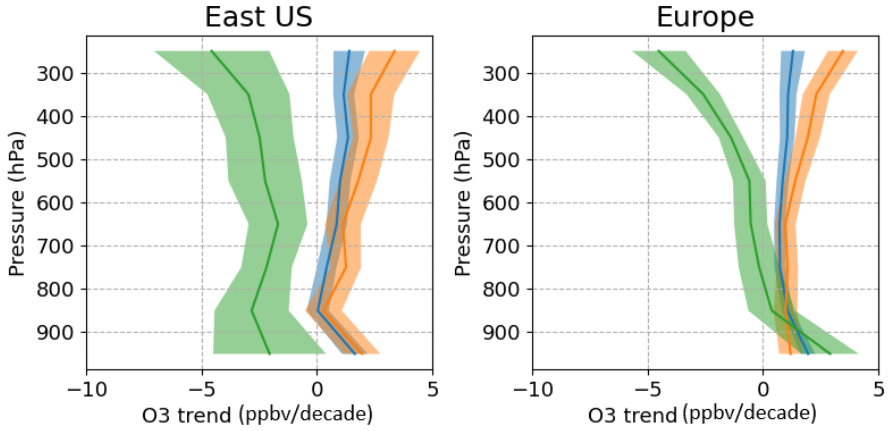

Figure 10. Profile of O_3 trends. Trends are calculated for three different periods: from 1994 to 2023 (blue), from 1994 to 2013 (orange) and from 2011 to 2023 (green) (in ppbv/yr).

spheric circulation, and consequently alterations in the exchange between these atmospheric layers, can significantly impact tropospheric O_3 trends (Williams et al., 2019; Li et al., 2024).

4 Conclusions

The analysis of 29 years IAGOS observation highlights that CO trends have become less and less negative until reaching a point where trends can no longer be detected in most regions. Over the past decade, the CO trend in the upper troposphere (UT) has been close to zero or even positive in certain regions, such as Europe. This trend may reflect nearly stagnant anthropogenic emissions in recent years, combined with an increase in CO emissions from wildfires and potential enhanced secondary production, both potentially linked to climate warming. Continued monitoring is essential to gain a clearer understanding of the recent evolution of CO levels.

Regarding O_3 trends, this analysis highlights that the most recent O_3 trends are found to be less pronounced than those diagnosed in earlier analyses. Trends calculated using nearly 30 years of data (1994–2023) are significantly weaker than those estimated by Cohen et al. (2018), which were based on measurements from 1994 to 2013 (e.g trends go from 0.32 ± 0.07 ppbv/yr in 1994/2013 to 0.16 ± 0.05 ppbv/yr in 1994/2023 for Europe and 0.34 ± 0.09 ppbv/yr and 0.17 ± 0.07 ppbv/yr in East US).

The recent context of O_3 levels in the upper troposphere (UT) is characterized by strong positive anomalies during the first half of the 2010s, followed by lower values in O_3 mixing ratios in the early 2020s. This latter phase is likely associated with the COVID-19 crisis, including widespread lockdowns and the resulting reduction in anthropogenic emissions. The contrast between these two periods appears to drive the negative O_3 trend observed across most regions (with medium to high certainty) during this timeframe.

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The post-2020 period also has a notable influence on the trends calculated using measurements from the entire period.

The O_3 trend in Europe, calculated from 1994 to 2019, is 0.24 $\pm$ 0.06 ppbv/yr, whereas the trend calculated up to 2023 is 0.16 $\pm$ 0.05 ppbv/yr, representing a decrease of 33%.

It appears that the effects of lockdowns, causing reduced industrial activity (and consequently lower anthropogenic precursor emissions), may have influenced O_3 levels for several years following 2020, although this cannot be confirmed with certainty.

The decline in O_3 since the 2010s is stronger in the upper troposphere than at lower altitudes over the European and Eastern US regions. Beyond the COVID-19 impact, multiple factors could explain the positive and negative anomalies observed during the 2010s and 2020.

This could be linked to changes in chemical regimes caused by variations in precursor emissions (Elshorbany et al., 2024), or to variations in stratospheric dynamics leading to modifications in stratosphere-troposphere exchange (Williams et al., 2019; Elshorbany et al., 2024; Li et al., 2024). Further studies will be necessary to attribute the causes of recent O_3 variations. Continued measurements are needed to determine whether this negative trend is merely related to a temporary negative anomaly in O_3 levels.

This decline in O_3 in the UT since the 2010s is likely the result of multiple contributing factors, including potential changes in O_3 production and destruction processes. Further model-based analyses will be required to fully understand the causes of the positive O_3 anomalies observed in the 2010s, as well as the subsequent decline. These investigations will help clarify the relative roles of dynamical, chemical, and emission-related processes in shaping these trends.

Modeling approaches will further enable us to quantify the contribution of natural precursor emissions and to evaluate the impact of temperature increases on photochemical processes, as well as on CO and O_3 values.

To determine whether the current observations reflect a temporary negative anomaly in O_3 levels or a sustained reduction in upper tropospheric O_3, continued IAGOS monitoring over the coming years will be essential. Updating this analysis in the future with 5-10 more years of observations will provide further information.

Further analyses using diverse and complementary observational records are essential to better constrain the direction and drivers of O_3 trends, especially in the context of ongoing emission changes and future climate scenarios.

Data availability. The IAGOS data (IAGOS, 2022) are available at the IAGOS data portal (https://doi.org/10.25326/20) and more precisely, the time series data are found at https://doi.org/10.25326/06 (Boulanger et al., 2018).

Appendix A: Data set and methodology

Author contributions. TL, VT, and BS designed the study. The IAGOS and SOFT-IO data were provided by BS, PW, YB, RB, DB, HC, JMC, JP, SC, PN and VT. The paper was written by TL and reviewed by VT, and BS, and edited and approved by all the authors.

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	1994-2013	2011-2023	1994-2023
East US	13 298	4 166	16 993
North Atl	11 550	3 541	14 661
Europe	29 064	14 739	41 877
W Med	4 266	3 886	7 714
Siberia	5 270	2 131	6 995
Mid East	5 565	3 605	8 724
South Asia	3 152	3 002	5 946
NE Asia	4 051	4 078	7 683
Tropical Africa	3 496	4 129	7 227

Table A1. Number of flights per regions and periods

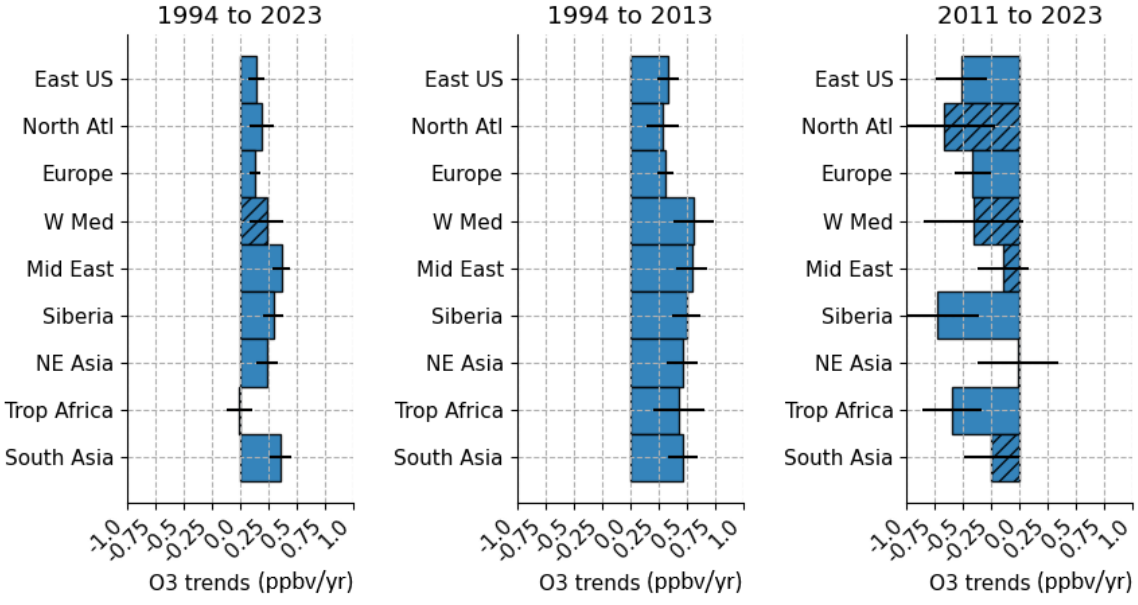

Figure A1. UT Trends of O_3 with a lower UT layer (220 to 350 hPa) (in ppbv/yr).

Competing interests. The authors declare that they have no conflict of interest.

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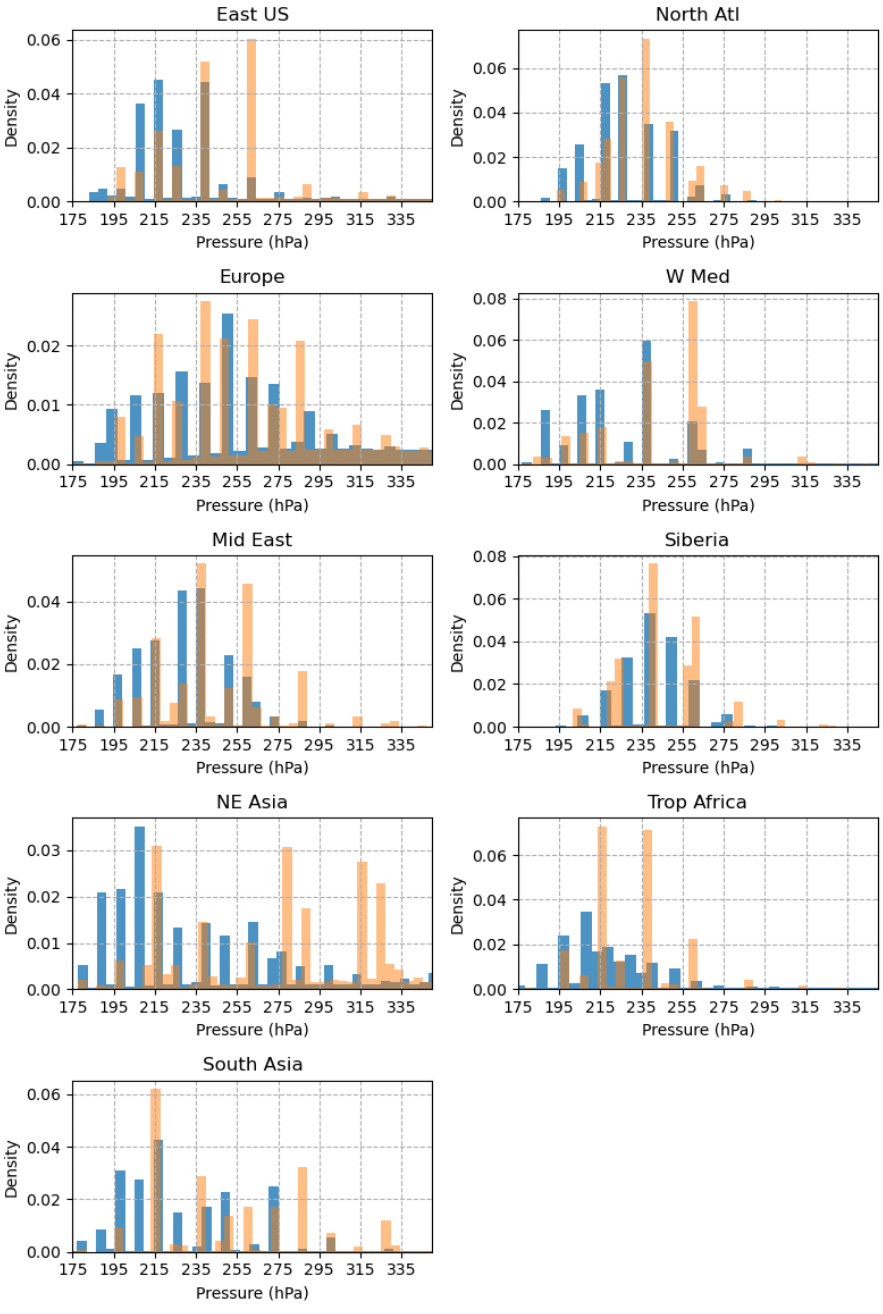

Figure A2. Pressure distribution before 2011 (in orange) and after 2011 (in blue).

345 IAGOS–DS and IAGOS–ERI. Additionally, IAGOS has been funded by INSU-CNRS (France), Météo-France, Université Paul Sabatier

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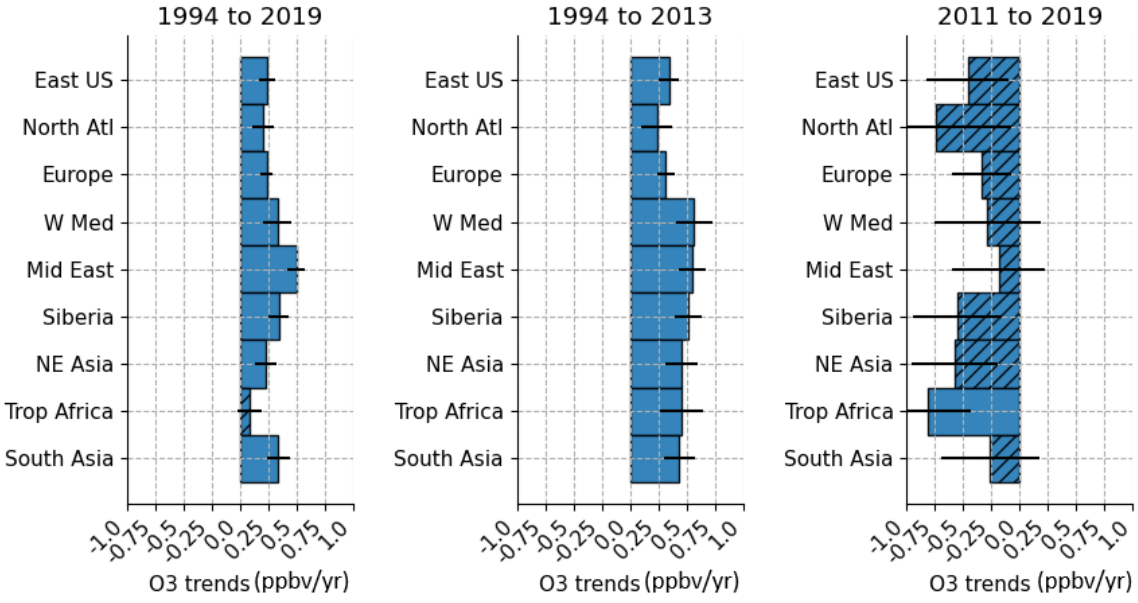

Figure B1. Upper Tropospheric trends of O_3 calculated from 1994 to 2019 (left), from 1994 to 2013 (middle) and from 2011 to 2019 (right) (in ppbv/yr). Hatched trends represent trends with low confidence (p value < 0.05 or SNR < 1.65).

(Toulouse, France) and Research Center Jülich (FZJ, Jülich, Germany). The IAGOS database is supported in France by AERIS (https://www.aeris-data.fr)

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