Ozone – 1 molecule, 100 yrs of history, multiple policy aspects

The new SCNAT ACP Factsheet on Ozone

Marloes Eeftens (Swiss TPH) • Luca Egli (PMOD/WRC) • Anina Gilgen (Agroscope) • **Jörg Klausen** (MeteoSwiss, lead) • Eliane Maillard-Barras (MeteoSwiss) • Clara Nussbaumer (ETH Zurich) • Rolf Rüfenacht (MeteoSwiss) • Patrick Schleppi (WSL) • Martin Steinbacher (Empa)

Why this factsheet, why now?


Vol. 21, No. 2, 2026

scnat

swiss academies factsheets

swiss-academies.ch

Ozone – A simple molecule with enduring impact on climate, air quality and health

Despite political efforts, the recovery of the stratospheric ozone layer is progressing only slowly, and ground-level concentrations regularly exceed regulatory limits. Further measures are needed to reduce the negative impacts on health, vegetation and climate. Global monitoring remains necessary. Switzerland contributes with the World's longest record of ozone observations that began 100 years ago in Arosa on 23 July 1926 and continue now in Davos.

Natural sunscreen and respiratory irritant

Ozone consists of three oxygen atoms bound together. It was discovered in 1839 by the German chemist Christian Friedrich Schönbein, who was working in the newly established Chemical Laboratory of the University of Basel. He later wrote to Justus von Liebig – another pioneer at the time – that he 'tends to believe that atmospheric ozone plays an important role in the Earth system.'[1]

The 'good' ozone

In the stratosphere (between about 15 and 50 km above ground, cf. fig. 1), the formation of ozone molecules removes dangerous incoming solar short-wave ultraviolet (UV-C) radiation. The resulting ozone layer absorbs further UV-B radiation and is a natural sunscreen that protects the Earth surface. Without ozone, terrestrial life as we know it could not have developed.

Over Antarctica, this protective shield is destroyed every year after polar sunrise in September. An 'ozone hole' forms due to a unique combination of cold temperatures, polar stratospheric clouds, and the remains of human-made chemicals, such as chlorofluorocarbons (CFC) that were mostly produced and used between 1950 and 1990. Ozone can also be depleted above Europe when Arctic air with low ozone concentrations reaches to mid-latitudes.[2,3] Then, higher UV radiation can cause unexpected sunburns.

The dominant ozone-depleting substance today is nitrous oxide (N_2O). Of it, 64% is emitted from natural sources (e.g. natural soils, oceans, wetlands), while 36% is of anthropogenic origin, mostly from food production.[4]

The 'bad' ozone

Some of the ozone in the troposphere (from the ground up to about 15 km above us, cf. fig. 1) mixes in from the stratosphere, but most of it is produced photochemically at ground-level when air pollutants react with sunlight. Ozone is a respiratory irritant, harmful to plants and a greenhouse gas. However, due to its reactivity, it also cleanses the atmosphere of other pollutants. Ground-level ozone can only be reduced indirectly by targeting the emissions of precursor substances.

Klausen J et al. (2026) Ozone – A simple molecule with enduring impact on climate, air quality and health. Swiss Academies Factsheets 21 (2)

100 years Swiss observations

Arosa 1926 → Davos today

1 molecule – 2 roles

UV shield aloft
Pollutant near us

Unfinished policy business

Ozone layer recovery slow
Surface ozone persists

The factsheet's central message

- **Long-term observations can lead to policy impact.**
- **Ozone layer on path to recovery.**
- **Surface ozone still an air quality issue.**
- **Continued monitoring still needed.**

Source: Klausen et al. (2026), Swiss Academies Factsheets 21(2).
DOI: doi.org/10.5281/zenodo.21060689

One molecule — two very different roles

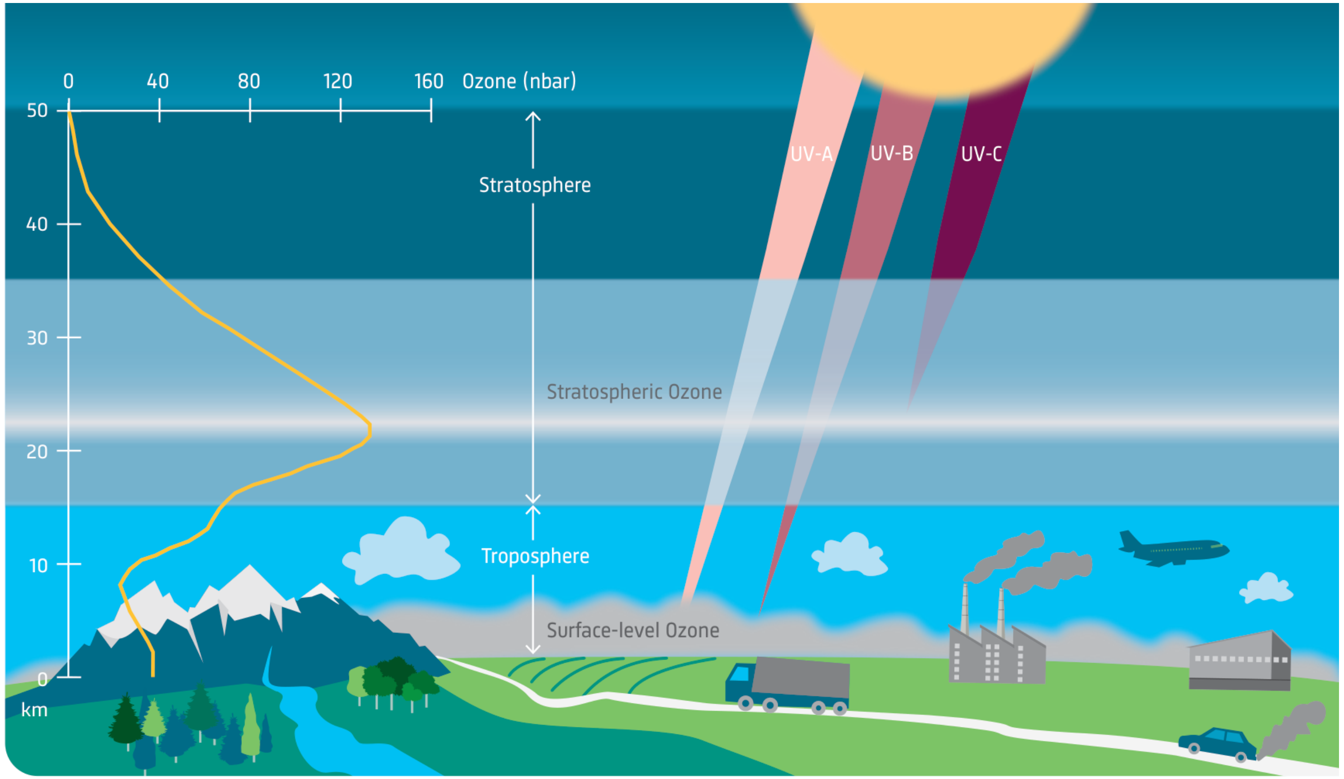


Figure 1: The mean ozone profile measured by balloon sondes and microwave radiometer in Payerne (VD) shows the stratospheric ozone layer between roughly 15 km and 35 km, with a maximum of ozone at about 22 km above ground. There, it is formed by highly energetic solar UV-C radiation. The ozone layer then absorbs most of the UV-B radiation, leaving the UV-A radiation to reach the Earth surface. Near the surface, ozone is formed Photochemically from air pollutants. Sources: MeteoSwiss, adapted from: NASA

STRATOSPHERE

Natural sunscreen
Absorbs UV-B and UV-C radiation;
essential for life at the surface.

NEAR THE SURFACE

Respiratory irritant;
Damages vegetation and crops;
also acts as a greenhouse gas.

Same molecule. Different chemistry, exposure and policy levers.

Arosa–Davos: 100 years of science-for-policy

23 July 1926

World’s longest continuous ground-based total-column ozone record begins

Figure 6: Daniel Chalonge, colleague of F. W. Paul Götz, on the terrace of the ‘Firnelicht’ house in Arosa in the early 1930s, between the Fabry-Buisson (predecessor of the Dobson spectrophotometer), the Chalonge, and the Féry spectrographs. Photo: unknown. Source: Photo archive MeteoSwiss

Arosa, early 1930s

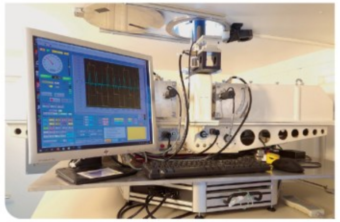


Figure 7: Automated Dobson instrument in Davos today. Photo: Franz Zeilinger

Davos today

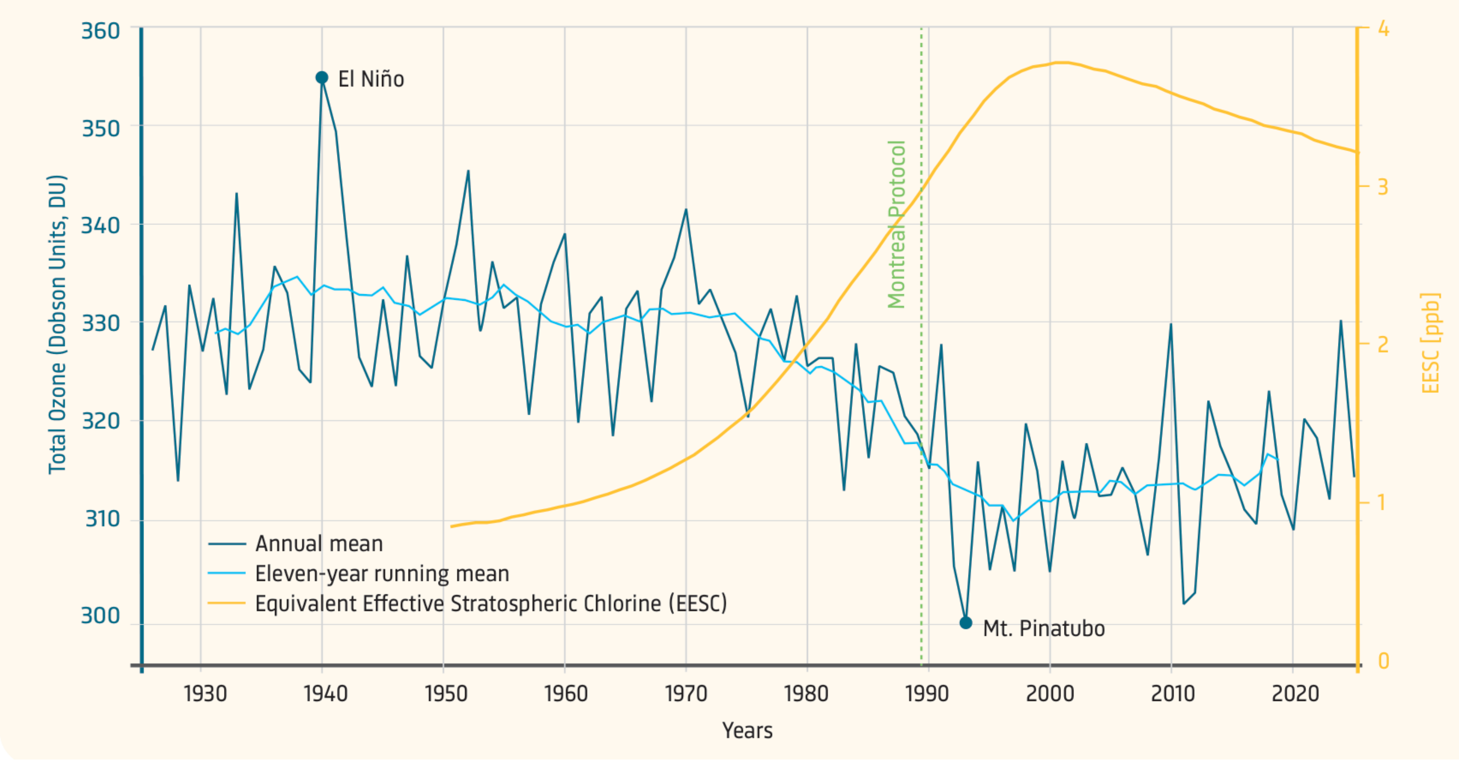
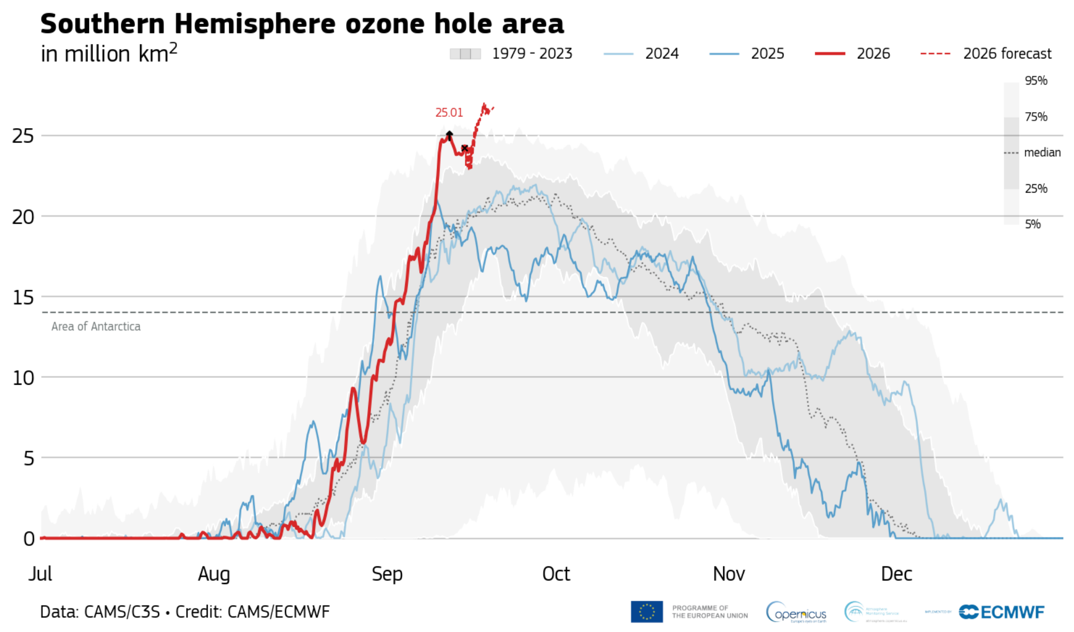
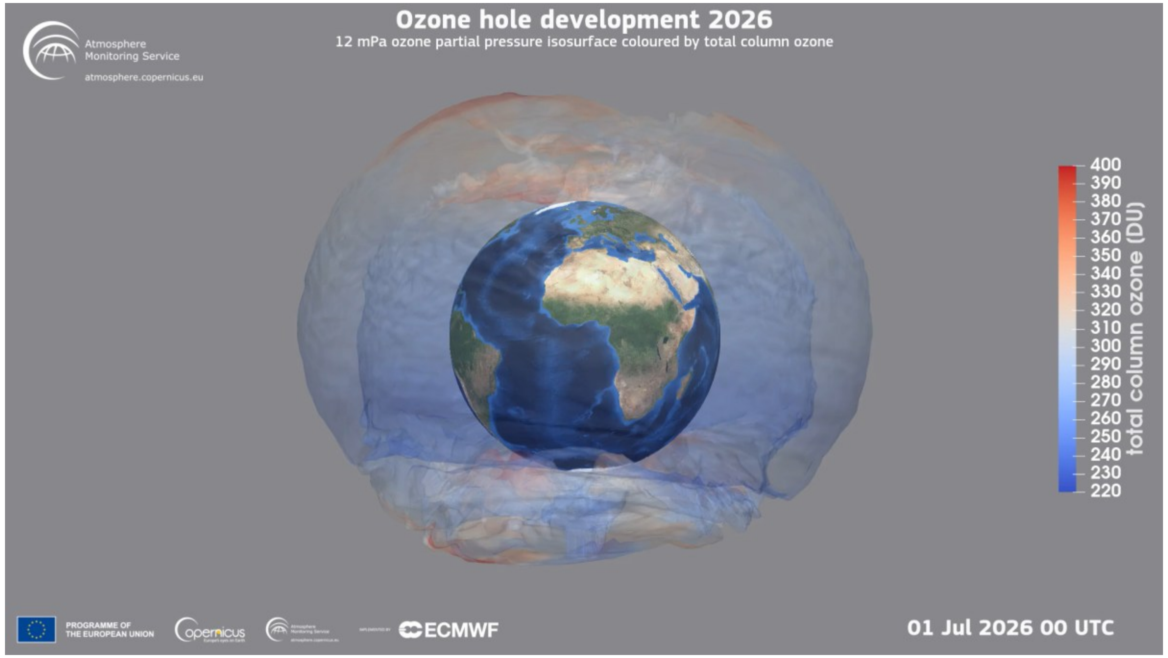


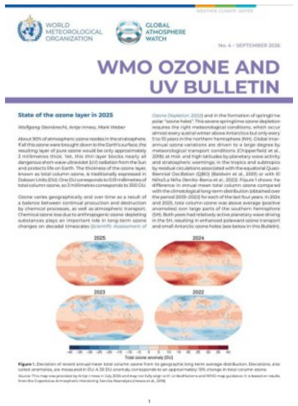
Figure 5: The world’s longest ground-based total column ozone (cf. box 1) observation time series from Arosa/Davos started in 1926. Higher ozone concentrations at the beginning are followed by rapid decline because of chlorine-containing ozone depleting substances. These were mainly emitted between the mid-1970s and the mid-1990s leading to a maximum of the Equivalent Effective Stratospheric Chlorine (EESC) around 2000 Ozone levels stabilized afterwards thanks to the effects of the Montreal Protocol and its amendments after 1989. Besides the long-term monitoring for trend analyses, such a long time series also captures rare weather anomalies like the extremely strong El Niño event in 1940/1941 or the effect of the volcanic eruption of Mt. Pinatubo in 1993. Figure adapted from MeteoSwiss

Long records are “critical infrastructure”
– they make policy effectiveness and unexpected change visible.

World Ozone Day on 16 Sep 2026







The Montreal Protocol works – recovery not done

>98%

controlled ODS reduction

Controlled production/consumption has fallen by more than 98%.

1-3% / decade

upper-stratospheric recovery

Observed since about 2000 between roughly 60°S and 60°N.

No significant trend

mid-latitude total column

At mid-latitudes, no significant total-column trend after 1995 to date.

Protocol adopted	Protocol enters into force	EESC peak	Expected recovery if compliance continues
1987	**1989**	**~2000**	**mid-century**

Lesson for air-quality: Policy can change atmospheric composition — but only when the relevant precursors and timescales are understood.

Source: SCNAT Factsheet 21(2), 2026, pp. 4–6;
WMO Scientific Assessment of Ozone Depletion (2022).

For air quality, the harder ozone problem is the ozone we breathe.

secondary pollutant

long-range transport

strongly weather-dependent

non-linear chemistry

Ground-level ozone is not emitted

NO_x
traffic · combustion

→

VOCs
solvents · vegetation

→

CH_4
hemispheric background

→

sunlight / heat
photochemistry

→

O_3
secondary pollutant

NON-LINEAR

O_3 can rise or fall when NO_x is reduced, depending on chemical regime and titration.

TRANSPORTED

Episodes reflect local production plus regional and hemispheric background.

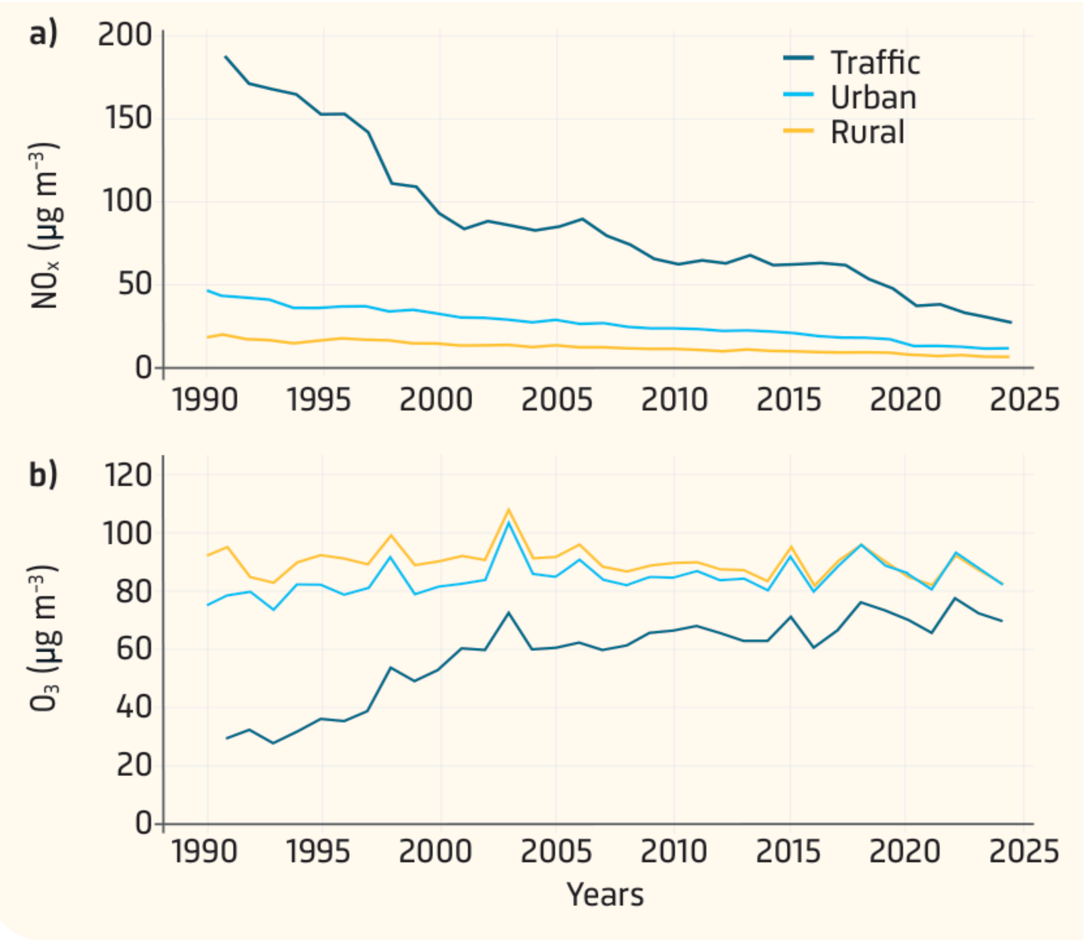
WEATHER-SENSITIVE

Sunshine, temperature, stagnation and boundary-layer dynamics strongly modulate O_3.

Control must therefore target precursors and exposure — not an “ozone source”.

Source: SCNAT Factsheet 21(2), 2026, p. 2; Nussbaumer et al., Atmos. Chem. Phys. 26, 5355–5373 (2026).

Swiss precursor controls worked, but ozone did not fall in parallel



NO_x

Strong decline at traffic, urban and rural NABEL sites since 1990.

O_3

Rural/urban summertime levels changed much less. **Roadside ozone increased as NO titration declined.**

The precursor signal is large; the ozone response is smaller, site-dependent and counter-intuitive.

Source: SCNAT Factsheet 21(2), 2026, Fig. 2; adapted from Nussbaumer et al. (2026).

The traffic-site “paradox” is mostly chemistry and titration

The old days: Freshly emitted NO

$$NO + O_3 \rightarrow NO_2 + O_2$$

Fresh NO removes ozone close to traffic.
This is “titration”, not lower regional photochemical production.

Strong local scavenging → low roadside O_3

Today: much less NO

less NO → less O_3 destroyed

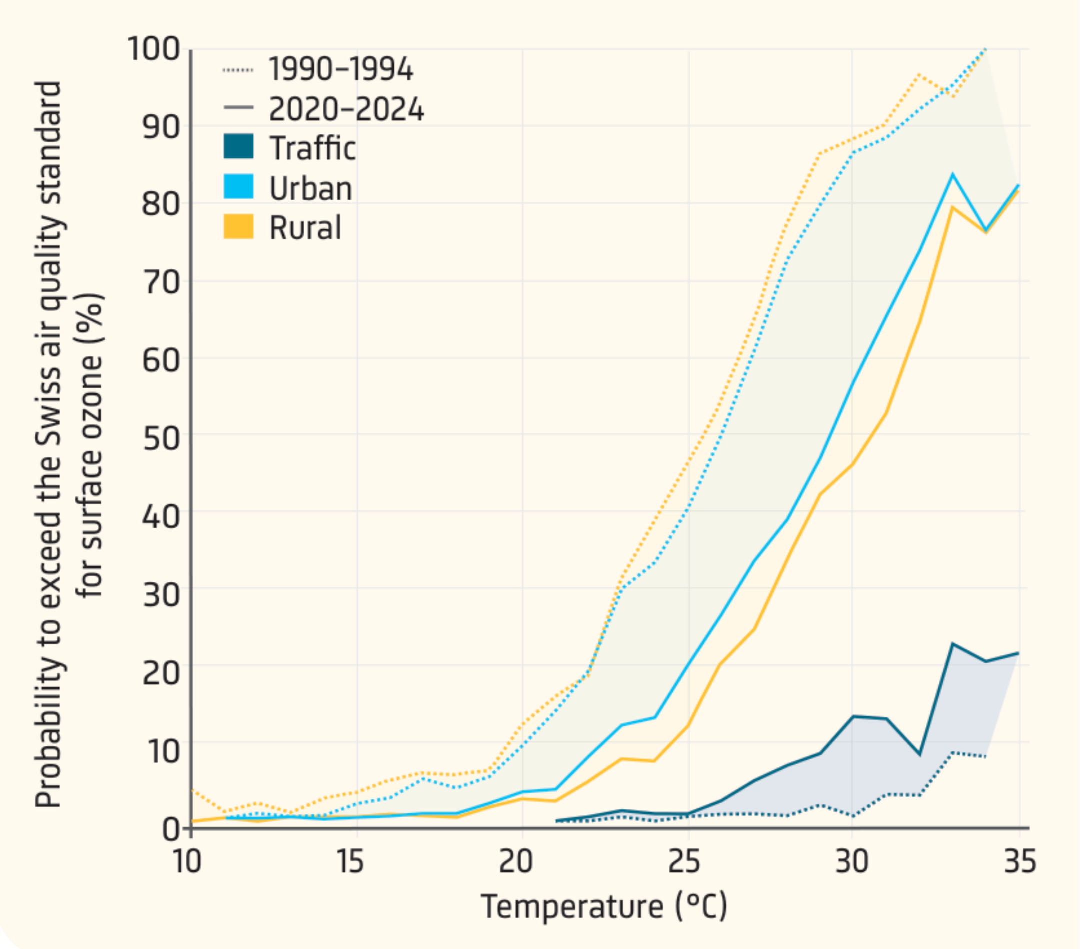
Roadside ozone can rise even while total oxidant emissions and exposure to NO_x fall.
The sign of the local O_3 trend is not a simple policy scorecard.

Less titration ≠ failed NO_x control

Nussbaumer et al.: 2000–2024 traffic O_3 increased while O_3 declined at rural sites.

Source: SCNAT Factsheet 21(2), 2026, pp. 2–3; Nussbaumer et al. (2026).

Climate change: Moving the goalposts



>25 °C

Exceedance probability rises steeply with temperature at urban and rural sites.

Changing since the 1990s

At traffic sites the high-temperature exceedance probability is now greater than in 1990–1994.

Climate implication

More hot, sunny and stagnant periods can erode gains from precursor reductions.

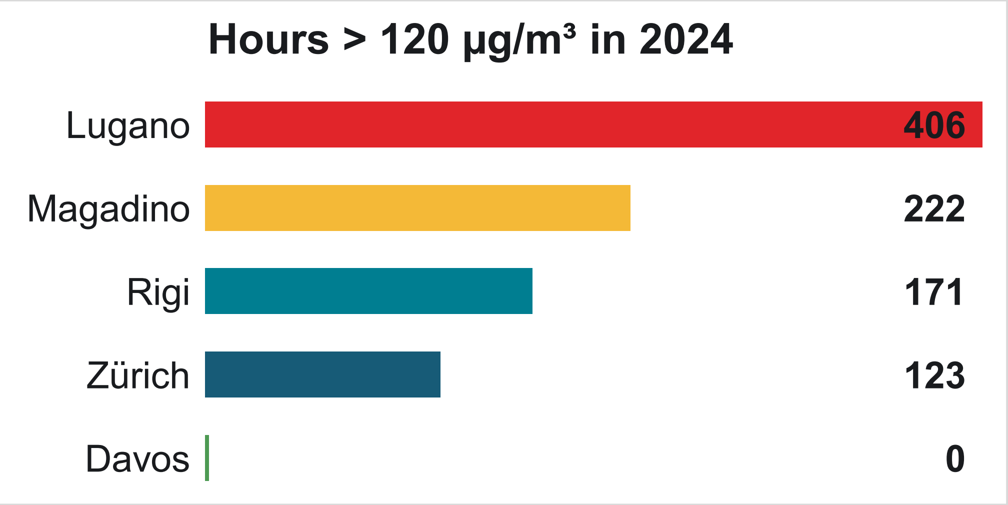
Source: SCNAT Factsheet 21(2), 2026, Fig. 3; Nussbaumer et al. (2026); Climate CH2025.

Ozone remains a Swiss compliance problem

All stations except 1
ozone limits exceeded
In 2024, ozone immission limits were exceeded at every NABEL station.

406 h
Lugano-Università
Hours above the 120 µg/m³ 1-hour limit; Magadino-Cadenazzo: 222 h.

192 / 173
µg/m³ peak 1-hour mean
Maximum in Lugano / maximum north of the Alps at Dübendorf-Empa.



What the NABEL network says

- The 120 µg/m³ 1-hour limit was exceeded at every NABEL station except Davos-Seehornwald.
- The monthly 98th-percentile limit (100 µg/m³) was still clearly exceeded across Switzerland.
- Summer peaks have declined over decades, but ozone remains the pollutant with persistent exceedances.

Success on PM and NO_2 does not imply success on O_3.

Source: BAFU/Empa, Nationales Beobachtungsnetz für Luftfremdstoffe NABEL — Messergebnisse 2024 (2025), pp. 3, 7–8.

A cantonal ozone episode is rarely a purely cantonal plume

LOCAL

fresh NO_x + VOCs chemistry + titration

minutes → hours

source / sink

→

REGIONAL

Photochemical production across Switzerland + neighbours

hours → days

production / transport

→

BACKGROUND

long-range transport + CH_4 + stratospheric contribution

weeks → months

baseline

Implication: local precursor control is necessary → regional and international coordination is unavoidable.

Sources: SCNAT Factsheet 21(2), 2026; BAFU/Empa NABEL 2024; UNECE/EMEP framework for long-range transboundary air pollution.

Europe in 2024: ozone remains the outlier

77.4%

stations above current LTO

Share of reporting stations above the current EU long-term objective for health in 2024.

78.2%

below 2030 target threshold

Share of reporting stations below the revised 2030 ozone target-value threshold in 2024.

LTO

no exceedance of 8-hour threshold of 120 µg/m³ .

2030 target

MDA8 >120 µg/m³ allowed on at most 18 days/year, averaged over 3 years.

The European picture is the same one Swiss networks see: large progress for several primary pollutants, but much smaller progress for ozone exposure.

Source: European Environment Agency, Air quality status in Europe 2026 — Ozone (official 2024 data).

Health protection is about exposure, not only hourly peaks

120 μg/m³

Swiss LRV

1-hour mean; useful for acute episodes and legal compliance.

100 μg/m³

WHO short-term AQG

Maximum *daily 8-hour mean*.

60 μg/m³

WHO peak-season AQG

Average of daily maximum 8-hour means during the six highest consecutive months.

These metrics are not directly comparable.

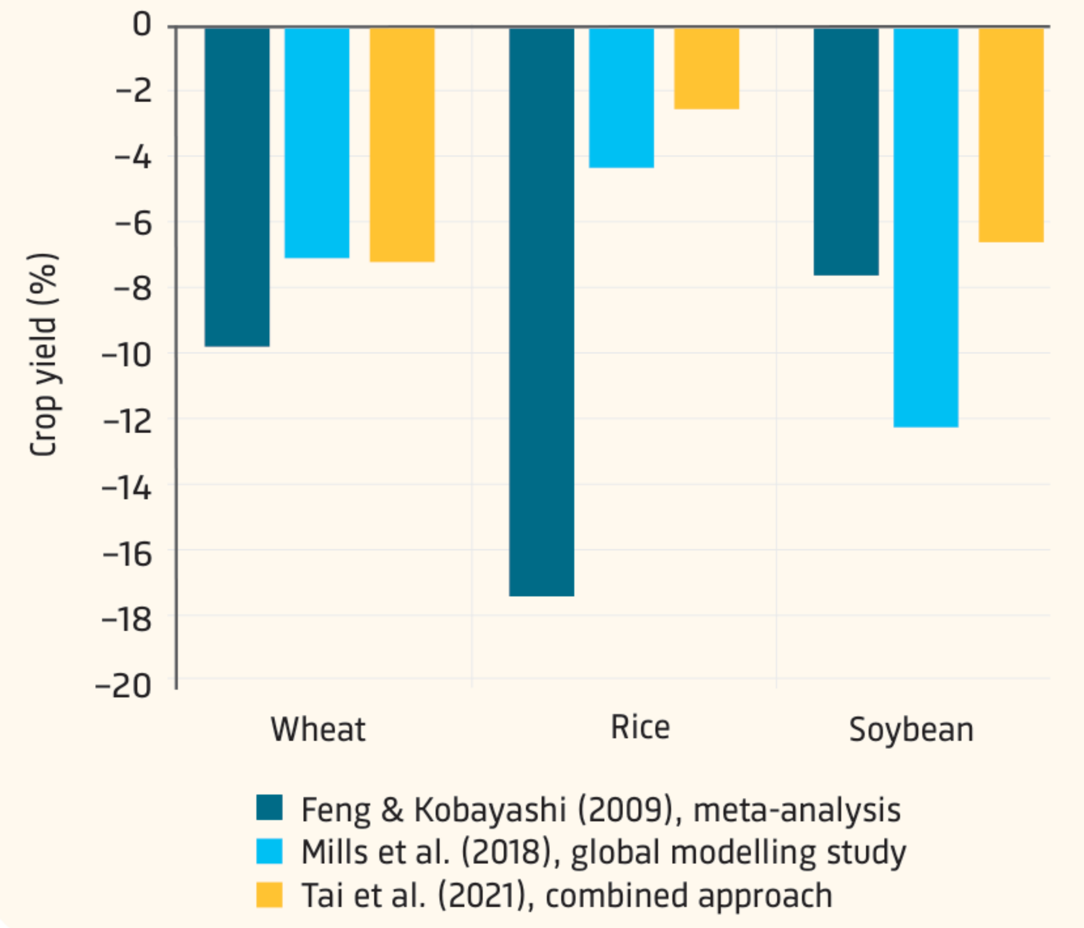
They answer different questions: acute peaks, daily-cycle exposure and chronic seasonal exposure.

For communication and health assessment,
"how often and for how long?" matters as much as "what was the maximum?".

EU 2030: MDA8 120 μg/m³, ≤18 exceedance days/year averaged over 3 years; long-term objective 100 μg/m³ by 2050.

Sources: Swiss Air Pollution Control Ordinance (LRV); WHO Global Air Quality Guidelines (2021); revised EU Ambient Air Quality Directive / EEA (2026).

Ozone damages vegetation – with measurable costs



6.7 Mt

European wheat, 2022
Estimated ozone-related yield loss; ≈ €1.3 billion.

3.2 Mt

European potatoes, 2022
Estimated ozone-related yield loss; ≈ €0.68 billion.

21.5%
of European agricultural land was exposed to ozone levels above the EU ozone target-value threshold for vegetation (2024).

Sources: SCNAT Factsheet 21(2), 2026, Fig. 4 and refs. 12–17; EEA ecosystem ozone indicator (2026).

What does this mean for cantonal air-quality management?

1 Keep reducing precursors

NO_x and VOC controls remain essential. At traffic sites, expect a transition period in which O_3 can rise as titration weakens.

2 Treat ozone as regional

Coordinate with Confederation and neighbouring countries; methane and imported background matter alongside local chemistry.

3 Integrate heat and health

Use heat-wave periods for targeted ozone communication and exposure reduction, especially for vulnerable groups and outdoor work.

4 Strengthen diagnostics

Interpret O_3 together with NO/NO_2, VOCs, meteorology and site type; distinguish peaks from seasonal exposure.

→ The objective is not just lower peaks – it is lower population and ecosystem exposure.

Synthesis from SCNAT Factsheet 21(2), 2026; Nussbaumer et al. (2026); NABEL 2024; EEA 2026.

Take-home messages

1. A century of Swiss observations shows that monitoring and international policy can work.

2. Swiss NO_x control has been highly effective — but surface ozone responds non-linearly and differently by site type.

3. Heat and climate change increase the risk that remaining precursor emissions still produce harmful ozone episodes.

4. **For cantons, the winning strategy is sustained precursor control + regional cooperation + exposure-oriented monitoring and communication.**

Source: Klausen et al. (2026), SCNAT ACP Ozone Factsheet; supporting evidence from NABEL, EEA and cited literature.

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Home Affairs FDHA
Federal Office of Meteorology and Climatology MeteoSwiss

MeteoSwiss
Operation Center 1
CH-8058 Zurich-Airport
T +41 58 460 91 11
www.meteoswiss.ch

scnat
swiss academy of sciences

Foto: Fabrizio Vignali (PMOD/WRC)