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# The Swiss National Air Pollution Monitoring Network (NABEL) – Bridging Science and Environmental Policy

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*Abstract:* Awareness of atmospheric air quality in Switzerland became a concern in the 1960s, as a result of which the Swiss National Air Pollution Monitoring Network (Nationales Beobachtungsnetz für Luftfremdstoffe - NABEL) was created in the 1970s. This paper describes the establishment and evolution of NABEL, emphasizing its important role in monitoring air quality in Switzerland, and its contribution to international observation networks and research. The network's history, legal framework, and measurement program are described, and exemplary time-series of air quality parameters are given. NABEL is an excellent example for reliable, long-term air quality monitoring and demonstrates the importance of such monitoring for air pollution control at both national and international levels.

**Keywords:** Aerosols · Air pollution control · Greenhouse gases · Trace gases

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## 1. Introduction and History

Air quality monitoring networks provide fundamental information on the state of air quality in a particular region. This information is essential for the development of efficient air pollution control policies that protect humans and the environment from any harmful effects of pollution. Air quality monitoring networks are designed for long-term and reliable operation.

In Switzerland, atmospheric air quality measurements began in the 1960s. This was the time when it became apparent that air pollution is not only causing concern locally but is also a national and international problem. Air pollutants are transported over long distances and can cause damage to the environment far away from where they are released. For example, the observed increase in acidification of the precipitation in Scandinavia was understood to be largely caused by long-range transport of sulfur dioxide ($SO_2$) and its atmospheric reaction product sulfate ($SO_4^{2-}$) from industrialized regions in western and central Europe. The concern about adverse impacts of long-range transport of air pollutants on natural ecosystems led to international research activities,

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and to a measurement program coordinated by the Organisation for Economic Cooperation and Development (OECD) carried out from 1972 to 1977. Switzerland, like most western and central European countries, participated in this program and committed itself to operate two measurement stations. Empa was commissioned by the Swiss Federal Office for the Environment (FOEN; at that time called the Federal Office for Environmental Protection) to set up and operate two measurement stations.

Those two sites were: Payerne (rural site on the Swiss plateau); and Jungfraujoch (high-alpine site 3,580 m asl.), and measurements were started in 1973. The OECD programme aimed to combine emission inventories, meteorological measurements, and dispersion modelling for estimation of the concentration fields of $SO_2$ and sulfate across Europe.[1] These estimations could then be compared with measurements from the network of stations. The results of the OECD programme demonstrated that internationally coordinated measures were necessary for mitigation of air pollution in Europe and led to the ratification of the Convention on Long-range Transboundary Air Pollution (CLRTAP) in 1979. The measurement network of the OECD program was then transferred to measurement activities in support of CLRTAP, within the European Monitoring and Evaluation Programme (EMEP).[2]

In 1976, the Swiss Federal Office for Environmental Protection launched the Swiss National Air Pollution Monitoring Network (NABEL) to establish a country-wide ground-based *in situ* observation network. Between 1978 and 1980, eight measurement stations were put into operation. The two sites of the OECD monitoring programme, Payerne and Jungfraujoch, were part of the new observation network. Shortly after, the relevant legal framework for NABEL was revised. The Environmental Protection Act (EPA) of 1983 and the Ordinance on Air Pollution Control (OAPC) of 1985 expanded and specified the requirements for measuring ambient air pollutant concentrations. In 1986, the Swiss Federal Council formulated the objectives of Swiss air pollution control for the coming years, and also specified the tasks of regulatory air pollutant measurements. At this point, the existing NABEL network did not meet the legal requirements since it was focused on rural and background environments. More specifically, NABEL in the 1980s was lacking highly polluted traffic locations in cities. Furthermore, the measurement programme was too limited in scope, lacking important air pollutants such as heavy metals and hydrocarbons. Therefore, the NABEL measurement programme was complemented by additional parameters, and the network was extended to 16 sites which were all in operation from 1992 onwards.

Fig. 1 provides a map of the 16 current NABEL sites, including their site type classification, *i.e.* the air pollution situation for which the site is representative. This concept of classifying stations into site types, is assuming that other locations in a comparable environment in the region of interest have very similar levels of air pollution. Comprehensive information about air quality in a region can then be obtained from a measurement network that covers all relevant site types. This implies that the NABEL sites primarily represent specific environments, and their geographic location (Fig. 1) is only of minor importance.

Eight of the NABEL stations represent rural and remote conditions. The observations at these sites are only slightly influenced by local sources and are representative of a larger region. This makes them essential for the global understanding of the atmospheric composition. Therefore, rural and remote NABEL sites are embedded in international activities such as the Global Atmosphere Watch (GAW) programme of the World Meteorological Organization (WMO),[3,4] the European research infrastructures Integrated Carbon Observation System (ICOS)[5] and the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS),[6] the Advanced Global Atmospheric Gases Experiment

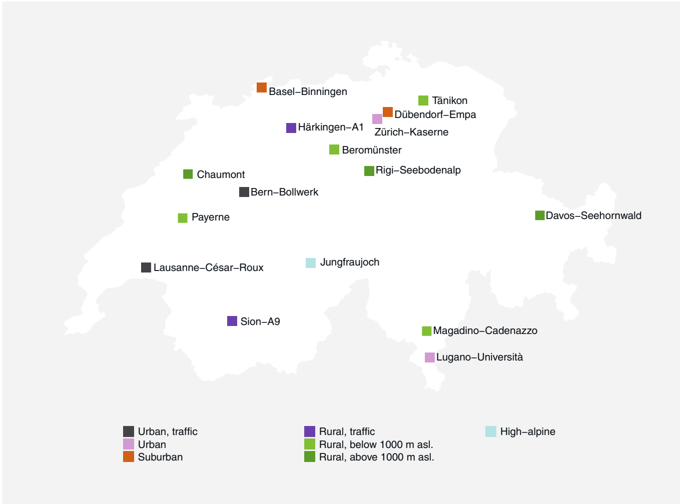


Fig.1. Location and type of sites of the NABEL air quality monitoring network.

(AGAGE),[7] and EMEP. The regional representativeness is well illustrated by EMEP, as this programme requires locations where the representativeness of the observations is larger than the resolution of the applied dispersion model. In this way, measurements can be used for model validation and thus contribute to the quantitative understanding of transboundary air pollution.[8]

It is noteworthy that the enforcement of air pollution control in accordance with the Swiss Environmental Protection Act is primarily the responsibility of the regional authorities (cantons). The cantons, therefore, run air quality monitoring networks for regulated air pollutants that are complementary to NABEL. The combination of NABEL and networks that are operated by cantons and cities provides a robust basis for the assessment of air quality in Switzerland.

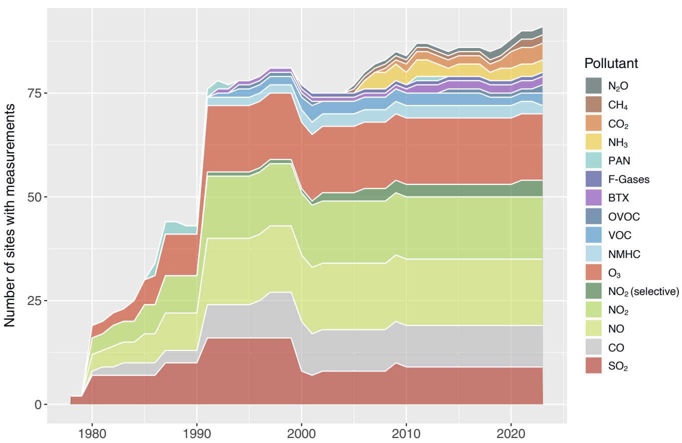


Fig. 2. Evolution of the NABEL measurement programme for gases since the beginning of the NABEL network in 1978. Abbreviations used: $N_2O$: nitrous oxide; $CH_4$: methane; $CO_2$: carbon dioxide; $NH_3$: ammonia; PAN: peroxyacetyl nitrate; F-Gases: halogenated hydrocarbons; BTX: benzene, toluene, xylene; OVOC: oxygenated volatile organic compounds; VOC: volatile organic compounds; NMHC: non-methane hydrocarbon; $O_3$: ozone; $NO_2$.selective: nitrogen dioxide measured with selective direct method; $NO_2$: nitrogen dioxide measured with indirect reference method; NO: nitrogen monoxide; CO: carbon monoxide; $SO_2$: sulfur dioxide.

Figs. 2 and 3 show the evolution of the NABEL measurement programme for gases (Fig. 2) and particulate air pollutants (Fig. 3) since its establishment in 1978. At the beginning of the NABEL network, the measurement program focused on the reactive gases CO, $NO_2$, $O_3$, and $SO_2$ due to the Swiss Ordinance on Air Pollution Control (OAPC), where air quality limit values for these compounds were defined. From the beginning of NABEL, accompanying scientific studies were carried out to improve the understanding of atmospheric processes. One example of this is the start of the measurements of peroxyacteyl nitrate (PAN) in the mid-1980s, a secondary pollutant that plays an important role in photochemical processes.[9]

In the 1990s, the importance of suspended fine particulate matter regarding the harmful effects of poor air quality on health was recognized.[10,11] This new insight led to the introduction of a limit value for the mass concentration of airborne particles with an aerodynamic diameter smaller than 10 micrometers (PM10) in 1998, and the need for a better understanding of atmospheric particulate matter. Mass concentration of particulate matter is only one metric for describing particulate air pollutants. In the following years, the NABEL measurement programme was therefore expanded and measurements of relevant indicators of the chemical and physical properties of particles in the atmosphere were included (Fig. 3).

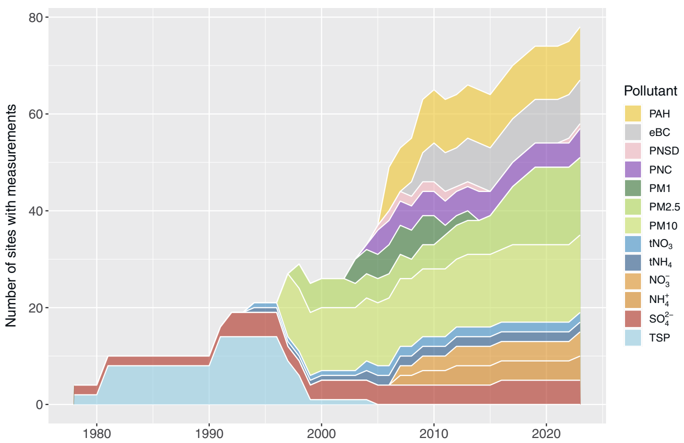


Fig. 3. Evolution of the NABEL measurement programme for particulate air pollutants since the beginning of the NABEL network in 1978. Abbreviations used: PAH: particulate polycyclic hydrocarbons; eBC: equivalent black carbon; PNSD: particle number size distribution; PNC: particle number concentration; PM1: particulate matter with an aerodynamic diameter smaller than 1 micrometer; PM2.5: particulate matter with an aerodynamic diameter smaller than 2.5 micrometer; PM10: particulate matter with an aerodynamic diameter smaller than 10 micrometer; $tNO_3$: sum of nitrate and nitric acid; $tNH_4$: sum of ammonium and ammonia; $NO_3^-$: nitrate; $NH_4^+$: ammonium; $SO_4^{2-}$: sulfate; TSP: total suspended particulate matter.

## 2. Quality Assurance and Quality Control

Implementation of appropriate quality assurance and quality control (QA/QC) measures is one of the key elements of NABEL and ensures consistent data of known and adequate quality. QA/QC measures include, among others, the use of type- approved or state-of-the-art instrumentation, traceability of the measurements to internationally accepted reference scales, the regular participation in round robin tests and interlaboratory comparisons, protocols, and tools for data processing and for the acquisition and storage of metadata. The details of QA/QC measures implemented in NABEL are described in a technical report.[12]

## 3. Reactive Gases

As described in the previous section, high emissions of sulfur dioxide and increased deposition of acidic sulfur compounds were of major environmental concern in the 1970s. Consequently, the measurement of ambient concentrations of sulfur dioxide and particulate sulfate was one of the most important activities at the start of the NABEL network in 1978 (Figs. 2 and 3). Fig. 4 shows the 50-year record of $SO_2$ and particulate sulfate at the rural site in Payerne, measured within the OECD programme and NABEL. These time series demonstrate the positive effect that can be achieved by environmental policy measures, in this case the series of measures to reduce $SO_2$ emissions, that have been gradually implemented in Switzerland and Europe in recent decades.

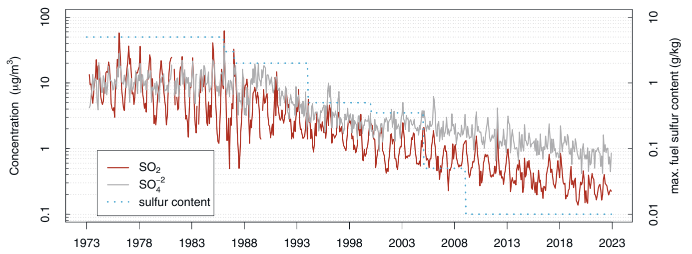


Fig. 4. Time series of monthly mean sulfur dioxide ($SO_2$) and particulate sulfate ($SO_4^{2-}$) concentrations at Payerne, a rural site on the Swiss plateau. The blue dashed line illustrates the maximum allowed sulfur content in diesel and fuel oil in Switzerland. Note the logarithmic scale, which on the one hand hides the very strong decrease of $SO_2$ and $SO_4^{2-}$, but on the other hand still shows the continuing decrease and the seasonal cycles at the low concentrations of the recent years. The sulfur content in diesel and fuel oil decreased stepwise from 5 g sulfur per kg fuel before 1986 to 0.01 g per kg since 2009.

The relative decrease over the considered time period is slightly stronger for $SO_2$ than for sulfate. This can be explained by the different origin and formation of the two species. $SO_2$ is directly emitted into the atmosphere while sulfate is mainly formed in the atmosphere through aqueous $SO_2$ oxidation. The formation of sulfate takes time (hours to days), so that the variability and trend of sulfate concentrations observed at Payerne reflect $SO_2$ emissions from large parts of Europe, whereas $SO_2$ concentrations in Payerne are dominated by local and regional emissions. Therefore, the temporal development of $SO_2$ and sulfate shown in Fig. 4 corroborates that control measures for $SO_2$ emissions were implemented in Switzerland and across Europe. Indeed, the first internationally binding commitments were adopted in 1985 with the Helsinki Protocol on the Reduction of Sulfur Emissions or their Transboundary Fluxes. Reductions in $SO_2$ emissions were then achieved mainly by the implementation of efficient emission control technologies, the upcoming usage of gas instead of coal in the early 1980s, the economic depression in Eastern Europe, and the desulfurization of fossil fuels in Western Europe in the 1990s.[13] The observations in Payerne are in line with the reported trends in $SO_2$ emissions in Switzerland and the surrounding European countries. According to OECD statistics, man-made $SO_2$ emissions in Switzerland decreased between 1990 and 2021 by 90%, while the decrease for all European OECD countries for the same time period was 82% (see https://stats.oecd.org). Across the whole NABEL network, relative changes in $SO_2$ and sulfate concentrations in Switzerland were on the order of 95% and 85 %, respectively.[14] Similarly to $SO_2$ and sulfate, excellent agreement between the estimated changes in Swiss emissions and the trend in ambient concentrations at NABEL sites was found for nitrogen oxide (NO+$NO_2$), NMHCs and PM10.[14]

The multi-decadal observations document a success story in air pollution control, from the diagnosing of an environmental concern, understanding the underlying processes, international negotiations and protocols, and implementation of emission reduction measures, ultimately leading to drastically lowered exceedances of critical loads of acidity, and to atmospheric $SO_2$ concentrations that are today well below the existing air quality limit values.

## 4. Aerosols – Atmospheric Particulate Matter

Epidemiological studies in the 1990s have shown that exposure to elevated mass concentrations of particulate matter (PM), *i.e.* PM10 and the finer fraction of particles with an aerodynamic diameter of less than 2.5 micrometers (PM2.5), are associated with health effects such as respiratory diseases, mortality, and impaired lung function.[10,11] Therefore, the implementation of measures to reduce PM concentrations and pollution has been a priority of air pollution control in Switzerland since the early 2000s, and an action plan to reduce particulate matter emissions was adopted in 2006.[15] At the European level, the revised Gothenburg Protocol, a protocol of the CLRTAP, which was amended in 2012, was another important step towards reducing particulate matter pollution in Switzerland and across Europe. In addition to commitments to reduce emissions of gaseous precursors of secondary PM ($SO_2$, $NO_X$, $NH_3$, and volatile organic compounds), the amended Gothenburg Protocol set legally binding targets by 2020 for reducing primary PM2.5 emissions in Europe to 22 % of 2005 levels (Switzerland 26 %).

With the measures taken at the national level and the European level to limit PM emissions, NABEL was given the task to assess their effects on air quality in Switzerland. This task was tackled by means of extended measurements (Fig. 3), trend analyses[8,16,17] and periodic studies on the chemical composition of PM10 and PM2.5, and estimation of the contributions of the main sources of atmospheric particulate matter.[18-21] A recent trend analysis study across European EMEP sites (including NABEL sites) shows substantial reductions of PM10 and PM2.5 concentrations in rural environments from 2000 to 2019.[8] On average, PM10 and PM2.5 have decreased by 1.8 % and 2.5 % per year since 2000, respectively. As with other air pollutants, the observed changes in PM10 and PM2.5 were in good agreement with the model calculations based on reported emission patterns across Europe. This confirms that the reduction commitments of the Gothenburg Protocol for 2020 have been met.[8]

A trend analysis for PM10 for the 1997 to 2016 period indicates a slightly greater decline of PM10 in Switzerland compared to the European average (2.6 % per year).[16] Measurements of the finer particle fraction PM2.5 were started in the NABEL network in 1998, and since 2018 there has been a legal limit value for the annual mean of PM2.5 in Switzerland. Similar to PM10, PM2.5 has strongly declined over the past 25 years and in the last few years ambient concentrations were compliant with the limit value throughout Switzerland (Fig. 5).

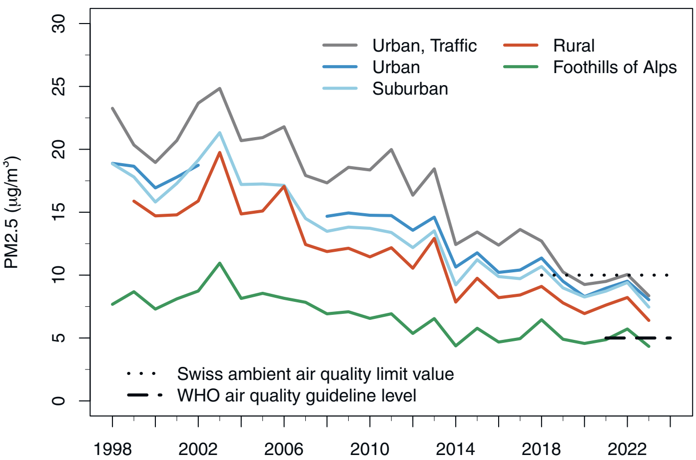


Fig. 5. Time series of annual mean PM2.5 concentrations at different site types in Switzerland. The Swiss ambient air quality limit value for PM2.5 that has been in force in Switzerland since 2018 and the air quality guideline level for annual PM2.5 as recommended by WHO in 2021 are shown.[22]

The Swiss action plan for the reduction of particulate matter from 2006 aimed to reduce emissions from all major sources.[15] However, a particular focus was on reducing emissions of soot or black carbon (BC), a component of PM that is classified as a carcinogen and therefore recognised as an important atmospheric pollutant to control. BC is, however, not a clearly defined component of PM and by convention is named equivalent black carbon (eBC), when collocated elemental carbon (EC) observations are used to transform light absorption measurements into BC mass.[23] In Switzerland, a number of measures to reduce soot emissions have been implemented since 2006. In particular, Euro emission standards for new vehicles and regulations for the emissions from construction machinery and other diesel engines have been tightened. The introduced regulations can only be met with diesel particulate filters (DPFs) and were expected to have a direct impact on BC concentrations in Switzerland. Since the beginning of the measurements of eBC in the NABEL network in 2008 (Fig. 3), the concentration of black carbon decreased until 2021 by about 5.3% per year at traffic locations, 4.5% per year at urban locations, and 3.5% per year in rural environments. The strong decrease in BC shows the effectiveness of the measures taken and was an important factor in the above-mentioned decrease in PM10 and PM2.5.

## 5. Greenhouse Gases

Greenhouse gases (GHGs) were not the primary focus of the NABEL measurement programme for a long time since these gases – per strict definition – are not considered as air pollutants. Greenhouse gases, at typical atmospheric concentrations, are not directly harmful to humans, materials, or ecosystems and, consequently, there are no legal air quality limit values for GHGs in the OAPC. However, air quality and climate are directly interrelated. On the one hand, anthropogenic and biogenic emissions are directly influenced by climate, and on the other hand air pollutants such as ozone, BC, or sulfate influence the radiation balance of the atmosphere and thus the climate.[24] NABEL has therefore been measuring GHGs at selected sites for many years (Fig. 2). In 2000, continuous measurements of halogenated organic compounds (*i.e.* ozone-depleting chlorofluorocarbons (CFCs) and their replacement products, hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs)) were started at Jungfraujoch.[25] These measurements aim at observing the abundance of gases regulated under the Montreal Protocol on ozone-depleting substances (ODS). In combination with atmospheric transport models, the observations also allow assessing Swiss and regional European emissions, locating sources and dominant source regions of non-$CO_2$ GHGs, and supporting the Swiss national emission inventory. Many of these halogenated organic substances are potent GHGs, accounting for approximately 11% of the total radiative forcing by long-lived GHGs.[26] Jungfraujoch was selected as the monitoring site for these activities due to its predominant exposure to pristine air masses representing the lower free troposphere and, consequently, the large spatial representativeness of the observations there. In 2005, the measurements were complemented by continuous observations of the three major long-lived GHGs: carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$). $CO_2$ measurements were initially operated by the University of Bern. Since 2010, $CO_2$ observations at Jungfraujoch are also run as part of the NABEL network.[27] Fig. 6 illustrates the increasing $CO_2$ trend since 2005, overlaid by a strong seasonal cycle due to the net uptake of $CO_2$

by the vegetation during the growing season. Recognizing the increasing public interest in GHGs and climate change, $CO_2$ observations were later extended to the NABEL sites at Haerkingen, Payerne, and Rigi-Seebodenalp. Since air pollutants and GHGs are partly co-emitted, and their atmospheric concentrations are governed by the same atmospheric mixing and transport, more advanced interpretation is possible when they are measured at the same location. The measurement of GHGs are also well embedded into international programs such as GAW, AGAGE, and ICOS, thus acknowledging the large-scale nature of climate change and ensuring a sound international coordination among the observations. With their solid expertise in long-term, high-quality observations, Swiss scientists play an essential role in know-how transfer and capacity building to support institutions in data-sparse regions, especially in developing countries. This paves the way towards a truly global coverage of such measurements, which is key to supporting the United Nations Framework Convention on Climate Change (UNFCCC) Parties, Global Stocktake (GST) actions of the Paris Agreement, and other stakeholders.

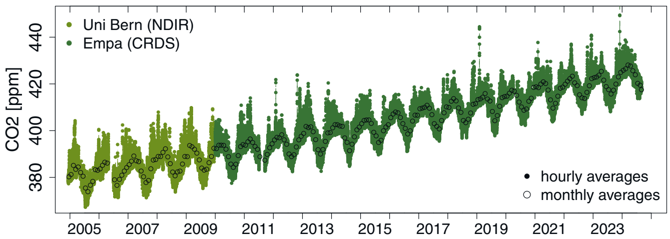


Fig. 6. Time series of hourly and monthly mean carbon dioxide ($CO_2$) mole fractions at Jungfraujoch.

## 6. Outlook and Conclusions

Since the Swiss air quality limit values were entered into force in 1985, concentrations of air pollutants have strongly decreased throughout Switzerland, which is due to the implementation of efficient emission reduction measures.[14] The current Swiss ambient air quality limit values, as defined in the Swiss Ordinance on Air Pollution Control (OAPC), largely correspond to the recommendations of the World Health Organization (WHO) in 2005, which are based on the knowledge of health impacts of the various air pollutants available at that time.[28] Over the past 20 years, there has been strong evidence that air pollutants have adverse health effects at significantly lower concentrations than concentrations recommended in 2005. Based on a comprehensive review of the current scientific literature, WHO has therefore updated its guidelines and lowered the recommended guideline values for air pollutants.[22] The Swiss Federal Environmental Protection Act stipulates the protection of the environment and the health of the entire population, including particularly sensitive population groups. This implies ambient air quality limit values at the level recommended in the WHO guidelines. The Federal Commission for Air Hygiene (FCAH) therefore recommends adapting the Ordinance on Air Pollution Control (OAPC), correspondingly.[29] Compliance with stricter legal limit values requires continuous and coordinated efforts to reduce air pollution at local, national, and international levels. Continuing efforts are particularly required for $NO_2$, PM2.5, and ozone, as the current pollution levels are in large parts of Switzerland well above the updated WHO guideline levels (Fig. 5).

Long-term, high-quality time series are a key element of national air pollution control. In addition, they play a decisive role at the international level, which is reflected by the numerous Swiss contributions to international atmospheric measurement and evaluation programs. And finally, observation-based emissions estimation is increasingly important in the context of international agreements and treaties. Switzerland was among the first, and is still one of the few countries that provide information to the United Framework Convention on Climate Change (UNFCCC) based on atmospheric observations and inverse modelling.[30] These estimates strongly rely on methods that are co-developed by Swiss scientists.[31,32] The concept of observation-based emissions estimates has also been adopted by the Global Greenhouse Gas Watch (G3W) of WMO, which promises to provide global emission fields to support the implementation of the Paris Agreement of the UNFCCC. G3W and similar endeavours to improve air quality and reduce the emissions of GHGs will continue to rely on long-term, continuous observations of the composition of the atmosphere.

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[1] B. Ottar, *Ambio* **1976**, *5*, 203, https://www.jstor.org/stable/4312216.

[2] K. Tørseth, W. Aas, K. Breivik, A. M. Fjæraa, M. Fiebig, A. G. Hjellbrekke, C. Lund Myhre, S. Solberg, K. E. Yttri, *Atmos. Chem. Phys.* **2012**, *12*, 5447, https://doi.org/10.5194/acp-12-5447-2012.

[3] P. Laj, A. Bigi, C. Rose, E. Andrews, C. Lund Myhre, M. Collaud Coen, Y. Lin, A. Wiedensohler, M. Schulz, J. A. Ogren, M. Fiebig, J. Gliß, A. Mortier, M. Pandolfi, T. Petäja, S.-W. Kim, W. Aas, J.-P. Putaud, O. Mayol-Bracero, M. Keywood, L. Labrador, P. Aalto, E. Ahlberg, L. A. Arboledas, A. Alastuey, M. Andrade, B. Artíñano, St. Ausmeel, T. Arsov, E. Asmi, J. Backman, U. Baltensperger, S. Bastian, O. Bath, J. P. Beukes, B. T. Brem, N. Bukowiecki, S. Conil, C. Couret, D. Day, W. Dayantolis, A. Degorska, K. Eleftheriadis, P. Fetfatzis, O. Favez, H. Flentje, M. I. Gini, A. Gregorič, M. Gysel-Beer, A. G. Hallar, J. Hand, A. Hoffer, C. Hueglin, R. K. Hooda, A. Hyvärinen, I. Kalapov, N. Kalivitis, A. Kasper-Giebl, J. E.Kim, G. Kouvarakis, I. Kranjc, R. Krejci, M. Kulmala, C. Labuschagne, H.-J. Lee, H. Lihavainen, N.-H. Lin, G. Löschau, K. Luoma, A. Marinoni, S. M. Dos Santos, F. Meinhardt, M. Merkel, J.-M. Metzger, N. Mihalopoulos, N. A. Nguyen, J. Ondracek, N. Pérez, M. Rita Perrone, J.-E. Petit, D. Picard, J.-M. Pichon, V. Pont, N. Prats, A. Prenni, F. Reisen, S. Romano, K. J. Sun, G. Titos, B. Toczko, T. Tuch, P. Tulet, P. Tunved, V. Vakkari, F. Velarde, P. Velasquez, P. Villani, S. Vratolis, S.-H. Wang, K. Weinhold, R. Weller, M. Yela, J. Yus-Diez, V. Zdimal, P. Zieger, and N. Zikova, *Atmos. Meas. Tech.* **2020**, *13*, 4353, https://doi.org/10.5194/amt-13-4353-2020.

[4] M. G. Schultz, H. Akimoto, J. Bottenheim, B. Buchmann, I. E. Galbally, S. Gilge, D. Helmig, H. Koide, A. C. Lewis, P. C. Novelli, C. Plass-Dülmer, T. B. Ryerson, M. Steinbacher, R. Steinbrecher, O. Tarasova, K. Tørseth, V. Thouret, C. Zellweger, *Elementa: Science of the Anthropocene* **2015**, *3*, https://doi.org/10.12952/journal.elementa.000067.

[5] J. Heiskanen, C. Brümmer, N. Buchmann, C. Calfapietra, H. Chen, B. Gielen, T. Gkritzalis, S. Hammer, S. Hartman, M. Herbst, I. A. Janssens, A. Jordan, E. Juurola, U. Karstens, V. Kasurinen, B. Kruijt, H. Lankreijer, I. Levin, M.-L. Linderson, D. Loustau, L. Merbold, C. L. Myhre, D. Papale, M. Pavelka, K. Pilegaard, M. Ramonet, C. Rebmann, J. Rinne, L. Rivier, E. Saltikoff, R. Sanders, M. Steinbacher, T. Steinhoff, A. Watson, A. T. Vermeulen, T. Vesala, G. Vitková and W. Kutsch, *Bull. Am. Met. Soc.* **2022**, *103*, E855, https://doi.org/10.1175/BAMS-D-19-0364.1.

[6] P. Laj, C. Lund Myhre, V. Riffault, V. Amiridis, H. Fuchs, K. Eleftheriadis, T. Petäjä, T. Salameh, N. Kivekäs, E. Juurola, G. Saponaro, S. Philippin, C. Cornacchia, L. A. Arboledas, H. Baars, A. Claude, M. De Mazière, B. Dils, M. Dufresne, N. Evangeliou, O. Favez, M. Fiebig, M. Haeffelin, H. Hermann, K. Höhler, N. Illmann, A. Kreuter, E. Ludewig, E. Marinou, O. Möhler, L. Mona, L. E. Murber, D. Nicolae, A. Novelli, E. O'Connor, K. Ohneiser, R. M. Petracca Altieri, B. Picquet-Varrault, D. van Pinxteren, B.

Pospichal, J.-P. Putaud, S. Reimann, N. Siomos, I. Stachlewska, R. Tillmann, K. A. Voudouri, U. Wandinger, A. Wiedensohler, A. Apituley, A. Comerón, M. Gysel-Beer, N. Mihalopoulos, N. Nikolova, A. Pietruczuk, A. Sauvage, J. Sciare, H. Skov, T. Svendby, E. Swietlicki, D. Tonev, G. Vaughan, V. Zdimal, U. Baltensperger, J.-F. Doussin, M. Kulmala, G. Pappalardo, S. S. Sunder, and M. Vana, *Bull. Am. Met. Soc*. **2024**, *105*, E1098, https://doi.org/10.1175/BAMS-D-23-0064.1.

[7] AGAGE, Advanced Global Atmospheric Gases Experiment, https://tolnet.larc.nasa.gov/missions/agage/.

[8] W. Aas, H. Fagerli, A. Alastuey, F. Cavalli, A. Degorska, S. Feigenspan, H. Brenna, J. Gliß, D. Heinesen, C. Hueglin, A. Holubová, J.-L. Jaffrezo, A. Mortier, M. Murovec, J.-P. Putaud, J. Rüdiger, D. Simpson, S. Solber, S. Tsyro, K. Tørseth, K. E. Yttri, *Aerosol and Air Quality Research* **2024**, *24*, 230237, https://doi.org/10.4209/aaqr.230237.

[9] S. Wunderli, R. Gehrig, *Atmos. Environ.. Part A. Gen. Topics* **1991**, *25*, 1599, https://doi.org/10.1016/0960-1686(91)90018-3.

[10] W. D. Douglas, C. A. Pope, X. Xu, J. D. Spengler, J. H. Ware, M. E. Fay, B. G. Ferris, F. E. Speizer, *New Eng. J. Med*. **1993**, *329*, 1753, https://doi.org/10.1056/NEJM199312093292401.

[11] C. Braun-Fahrländer, J. C. Vuille, F. H. Sennhauser, U. Neu, T. Künzle, L. Grize, M. Gassner, C. Minder, C. Schindler, H. S. Varonier, and B. Wüthrich, *Am. J. Resp. Crit. Care Med*. **1997**, *155*, 1042, https://doi.org/10.1164/ajrccm.155.3.9116984.

[12] Empa, 'Technischer Bericht zum Nationalen Beobachtungsnetz für Luftfremdstoffe (NABEL)', Empa, Materials Science and Technology, Duebendorf, **2024**.

[13] V. Vestreng, G. Myhre, H. Fagerli, S. Reis, L. Tarrasón, *Atmos. Chem. Phys*. **2007**, *7*, 3663, https://doi.org/10.5194/acp-7-3663-2007.

[14] BAFU, 'Luftqualität 2022. Messresultate des Nationalen Beobachtungsnetzes für Luftfremdstoffe (NABEL)', Bundesamt für Umwelt (BAFU) und Eidgenössische Materialprüfungs- und Forschungsanstalt (Empa), Bern, **2023**.

[15] EKL, 'Feinstaub in der Schweiz. Status-Bericht der Eidg. Kommission für Lufthygiene (EKL)'Bern, **2007**.

[16] S. K. Grange, D. C. Carslaw, A. C. Lewis, E. Boleti, C. Hueglin, *Atmos. Chem. Phys*. **2018**, *18*, 6223, https://doi.org/10.5194/acp-18-6223-2018.

[17] S. K. Grange, H. Lotscher, A. Fischer, L. Emmenegger, C. Hueglin, *Atmos. Meas. Tech*. **2020**, *13*, 1867, https://doi.org/10.5194/amt-13-1867-2020.

[18] C. Hueglin, R. Gehrig, M. Gysel, U. Baltensperger, C. Monn, H. Vonmont, *Atmos. Environ*. **2005**, *39*, 637, https://doi.org/10.1016/j.atmosenv.2004.10.027.

[19] M. F. D. Gianini, R. Gehrig, A. Fischer, A. Ulrich, A. Wichser, C. Hueglin, *Atmos. Environ*. **2012**, *54*, 97, https://doi.org/10.1016/j.atmosenv.2012.02.037.

[20] M. F. D. Gianini, A. Fischer, R. Gehrig, A. Ulrich, A. Wichser, C. Piot, J. L. Besombes, C. Hueglin, *Atmos. Environ*. **2012**, *54*, 149, https://doi.org/10.1016/j.atmosenv.2012.02.036.

[21] S. K. Grange, A. Fischer, C. Zellweger, A. Alastuey, X. Querol, J.-L. Jaffrezo, S. Weber, G. Uzu, C. Hueglin, *Atmos. Environ.: X* **2021**, *12*, 100145, https://doi.org/10.1016/j.aeaoa.2021.100145.

[22] WHO, 'WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide', World Health Organization, Geneva, **2021**.

[23] A. Petzold, J. A. Ogren, M. Fiebig, P. Laj, S. M. Li, U. Baltensperger, T. Holzer-Popp, S. Kinne, G. Pappalardo, N. Sugimoto, C. Wehrli, A. Wiedensohler, X.-Y. Zhang, *Atmos. Chem. Phys*. **2013**, *13*, 8365, https://doi.org/10.5194/acp-13-8365-2013.

[24 ] D. L. Schumacher, J. Singh, M. Hauser, E. M. Fischer, M. Wild, S. I. Seneviratne, *Commun. Earth Environ*. **2024**, *5*, 182, https://doi.org/10.1038/s43247-024-01332-8.

[25] S. Reimann, M. K. Vollmer, D. Folini, M. Steinbacher, M. Hill, B. Buchmann, R. Zander, E. Mahieu, *Sci. Total Environ*. **2008**, *391*, 224, https://doi.org/10.1016/j.scitotenv.2007.10.022.

[26] WMO, 'The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2022'Geneva, **2023**.

[27] M. F. Schibig, M. Steinbacher, B. Buchmann, I. T. van der Laan-Luijkx, S. van der Laan, S. Ranjan, M. C. Leuenberger, *Atmos. Meas. Tech*. **2015**, *8*, 57, https://doi.org/10.5194/amt-8-57-2015.

[28] WHO, 'WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide : global update 2005 : summary of risk assessment', World Health Organization, Geneva, **2006**.

[29] EKL, 'Die neuen WHO-Luftqualitätsrichtwerte 2021 und ihre Bedeutung für die Schweizer Luftreinhalte-Verordnung', Eidgenössische Kommission für Lufthygiene (EKL) Bern, **2023**.

[30] FOEN, 'Switzerland's Greenhouse Gas Inventory 1990–2022. National Inventory Document'Bern, **2024**.

[31] S. Henne, D. Brunner, B. Oney, M. Leuenberger, W. Eugster, I. Bamberger, F. Meinhardt, M. Steinbacher, L. Emmenegger, *Atmos. Chem. Phys*. **2016**, *16*, 3683, https://doi.org/10.5194/acp-16-3683-2016.

[32] M. Steiner, W. Peters, I. Luijkx, S. Henne, H. Chen, S. Hammer, D. Brunner, *Atmos. Chem. Phys*. **2024**, *24*, 2759, https://doi.org/10.5194/acp-24-2759-2024.