Horizontal visibility across Switzerland between 1980 and 2018

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Contents

Abstract

Horizontal visibility is a conspicuous atmospheric parameter and good visibility is universally desirable. Atmospheric particulate matter (PM) and relative humidity (RH) are the main drivers of atmospheric visibility while the influence of gases on visibility is small or even negligible. Atmospheric PM affects visibility through light scattering and light absorption. The influence of RH on visibility is caused by water uptake of PM under humid conditions which results in an increase of scattering efficiency for the larger particles. As a result of the abatement policies that have been implemented at regional, national, and European level in the past years, atmospheric PM concentrations have decreased across Switzerland over time. Therefore, associated increases in horizontal visibility are to be expected. The aim of this study is to investigate the long-term trend of horizontal visibility in Switzerland and to confirm that the efforts taken to abate emissions of air pollutants have had a positive effect on atmospheric visibility.

Visibility observations from 11 sites across Switzerland between 1980 and 2018 were analysed alongside surface meteorological and air quality data. The results indicated that mean visibility is significantly increasing across most of Switzerland at rates between 64 and 440 meters per year. Additionally, the occurrence of "low visibility days" are decreasing significantly, while extremely clear conditions are significantly increasing in most locations. Visibility was found to be negatively correlated with RH, *i.e.*, the more the air is saturated, the poorer the visibility. For many locations in Switzerland, a progressive increase in visibility across all RH conditions was observed. Visibility across Switzerland also showed a clear, inverse relationship to ambient PM concentrations where as PM concentrations decreased, visibility increased. This relationship was not as clear for mountainous locations when compared to sites located at lower altitude.

The observed increase in horizontal visibility under dry conditions can be explained by the reduction of atmospheric PM in Switzerland during the past decades, this is because horizontal visibility is under these conditions dominated by the interaction of light with fine particulate matter. This conclusion is also supported by the mean weekly cycle of horizontal visibility. Horizontal visibility is on average highest on Sundays, when emissions of particulate matter and other air pollutants are lowest due to reduced industrial and business activities. Interestingly, the reduced emissions at the weekend also affect the visibility at the beginning of the week where on Mondays, the horizontal visibility is on average greater than on the following working weekdays. Due to the time required for the formation of secondary particulate matter, the reduced emissions at the weekend also lead to lower average atmospheric PM levels on Mondays.

The linkage between air quality and visibility is clear from theoretical considerations and from the descriptive analysis performed in this study. However, formalisation of the linkage between air quality and visibility might be a worthy avenue for the future and statistical or machine learning modelling are potential approaches for this work. The analysis of the data for detection of changes in horizontal visibility required careful evaluation of the observational record to ensure the results were both valid and useful.

Zusammenfassung

Die grösste horizontale Entfernung, bei der im Gelände ein Objekt vor einem Hintergrund erkannt werden kann, wird als horizontale Sichtweite bezeichnet. Die horizontale Sichtweite wird an 25 Standorten des manuellen Beobachtungsnetzes der MeteoSchweiz mehrmals täglich mittels Augenbeobachtungen bestimmt. Teilweise werden ergänzend auch automatische Messsysteme eingesetzt. Im Rahmen dieser Studie wurden die vorhandenen langjährigen Beobachtungen ausgewertet und die zeitliche Entwicklung der horizontalen Sichtweite in der Schweiz für den Zeitraum von 1980 bis 2018 untersucht. Mittels Anwendung eines adaptiven Kolmogorov-Zurbenko Tiefpassfilters wurde die Homogenität der vorhandenen Messreihen geprüft. Die Zeitreihen von 11 Standorten zeigten eine Datenqualität, die für die Untersuchung von langjährigen Veränderungen geeignet erschien. Die Zeitreihen dieser Auswahl von 11 Stationen wurden für diese Studie verwendet.

Die horizontale Sichtweite hängt hauptsächlich von der Aerosol- bzw. Feinstaubbelastung sowie der relativen Feuchte ab. Gase haben dagegen einen kleinen und vielerorts vernachlässigbaren Einfluss auf die Sichtweite. Atmosphärische Feinstaubpartikel beeinflussen die Sichtweite durch Lichtstreuung und Lichtabsorption. Der Einfluss der relativen Feuchte resultiert aus der Wasserlöslichkeit von atmosphärischen Feinstaubpartikeln: Bei hohen Luftfeuchten nehmen Feinstaubpartikel Wasser auf, sie werden grösser und können dadurch effizienter Licht streuen.

In der Schweiz sowie in den Nachbarländern wurden in den letzten Jahren und Jahrzehnten eine Reihe von Massnahmen zur Reduktion der Emissionen von Feinstaub sowie von gasförmigen Vorläufern von sekundärem Feinstaub umgesetzt. Als Folge der Umsetzung dieser Massnahmen hat die Feinstaubbelastung in der Schweiz in den vergangenen dreissig Jahren kontinuierlich abgenommen. Aufgrund des beschriebenen Zusammenhangs zwischen Feinstaubbelastung und horizontaler Sichtweite muss erwartet werden, dass die Verbesserung der Luftqualität zu einem Anstieg der horizontale Sichtweite geführt hat. Das Ziel dieser Studie ist es, Veränderungen der horizontalen Sichtweite in der Schweiz zu dokumentieren und zu erklären.

Die Auswertungen der Zeitreihen von 11 Stationen zeigen, dass die mittlere horizontale Sichtweite in der Schweiz im Zeitraum von 1980 bis 2018 je nach Standort zwischen 64 und 440 Meter pro Jahr zugenommen hat. Zudem hat die Häufigkeit von Bedingungen mit geringer horizontaler Sichtweite und Nebel während dieser Zeit signifikant abgenommen. Bedingungen mit sehr grosser horizontaler Sichtweite treten dagegen an den meisten Standorten häufiger auf.

Die Augenbeobachtungen zeigen einen klaren negativen Zusammenhang zwischen der horizontalen Sichtweite und der relativen Feuchte. Bei trockenen Bedingungen sind die horizontalen Sichtweiten am grössten, bei hohen Feuchten ist die Sichtweite dagegen gering. Wird die zeitliche Entwicklung der horizontalen Sichtweite getrennt für trockene Bedingungen untersucht, so zeigt sich, dass die horizontale Sichtweite unter diesen Bedingungen an den meisten Stationen zugenommen hat. Da bei trockenen Bedingungen die Sichtweite durch die Wechselwirkung des Lichtes mit Feinstaubpartikel dominiert wird, lässt sich der Anstieg der horizontalen Sichtweite auf die Abnahme der Feinstaubbelastung zurückführen.

Diese Schlussfolgerungen werden auch durch die mittleren Wochengänge der horizontalen Sichtweite unterstützt. Die horizontale Sichtweite ist sonntags im Mittel am grössten, wenn aufgrund von reduzierten Aktivitäten die Emissionen von Feinstäuben und anderen Luftschadstoffen am geringsten sind. Interessanterweise wirken sich die verminderten Emissionen am Wochenende auch auf die Sichtweiten am Wochenanfang aus: Montags ist die horizontale Sichtweite im Mittel grösser als an den nachfolgenden Werktagen. Aufgrund der für die Bildung von sekundären Feinstäuben benötigten Zeit, führen die reduzierten Emissionen am Wochenende auch montags zu tieferen mittleren Feinstaubbelastungen.

Zum Schutz der Gesundheit der Menschen und der Umwelt wurden in der Schweiz sowie in den Nachbarländern eine Vielzahl von Massnahmen zur Reduktion der Emissionen von Luftschadstoffen umgesetzt. Diese Massnahmen führten zu einer deutlichen Verbesserung der Luftqualität und hatten darüber hinaus positive Auswirkungen auf die Sichtweiten in der Schweiz.

Résumé

La visibilité horizontale désigne la distance maximale à laquelle il est possible d'identifier un objet dans son contexte. Elle est estimée plusieurs fois par jour par des observations visuelles sur 25 sites du réseau d'observations humaines de MétéoSuisse. Parfois, des systèmes de mesures automatiques sont également utilisés à titre complémentaire. La présente étude porte sur l'évaluation des observations réalisées depuis de nombreuses années et sur l'analyse de l'évolution de la visibilité horizontale en Suisse entre 1980 et 2018. Le filtre passe-bas adaptatif Kolmogorov-Zurbenko a été utilisé pour vérifier l'homogénéité des séries de mesures disponibles.

Les séries temporelles issues de onze sites présentaient une qualité des données semblant convenir pour examiner les modifications au fil des années. Elles ont donc été utilisées pour cette étude.

La visibilité horizontale dépend essentiellement de la charge en poussières fines ou aérosols ainsi que de l'humidité relative de l'air. En revanche, les gaz ont la plupart du temps une incidence faible, voire négligeable, sur la visibilité. Les particules fines en suspension dans l'atmosphère agissent sur la visibilité par diffusion ou absorption de la lumière. L'influence de l'humidité relative résulte du caractère hydrosoluble des particules en suspension : en cas de forte humidité, celles-ci se gorgent d'eau, grossissent et dispersent ainsi mieux la lumière.

En Suisse et dans les pays voisins, un certain nombre de mesures ont été prises au cours des dernières années et décennies afin de réduire les émissions de poussières fines et de précurseurs gazeux des poussières secondaires. Grâce à ces initiatives, la charge en poussières fines n'a cessé de diminuer depuis 30 ans en Suisse. Compte tenu de la corrélation entre la charge en poussières et la visibilité, il faut s'attendre à ce que l'amélioration de la qualité de l'air se répercute sur la visibilité horizontale. Cette étude entend documenter les modifications de la visibilité horizontale en Suisse et fournir les explications correspondantes.

Les analyses des séries temporelles issues de onze sites montrent que la visibilité horizontale moyenne en Suisse a augmenté entre 1980 et 2018 de 64 à 440 mètres par an selon les endroits. En outre, les jours de faible visibilité horizontale et de brouillard ont été nettement plus rares pendant cette période, alors que la majeure partie des sites ont enregistré plus fréquemment une excellente visibilité horizontale.

Les observations visuelles mettent en évidence une corrélation clairement négative entre la visibilité horizontale et l'humidité relative. La visibilité horizontale est maximale en présence de conditions climatiques sèches et nettement plus faible en cas de forte humidité. Si l'on étudie l'évolution de la visibilité horizontale sur la période donnée mais uniquement en con-

ditions climatiques sèches, on constate une progression sur la plupart des sites. Comme la visibilité est fonction, par temps sec, de l'interaction de la lumière avec les particules fines en suspension, l'amélioration de la visibilité horizontale est imputable à la baisse de la charge de l'air en poussières fines.

Ces conclusions sont étayées par l'évolution moyenne de la visibilité horizontale sur la semaine. En effet, la visibilité horizontale est généralement meilleure le dimanche, lorsque les émissions de poussières fines et d'autres polluants atmosphériques sont les plus faibles en raison d'une activité ralentie. Il est intéressant de voir que le recul des émissions le week-end a aussi une incidence sur les valeurs de la visibilité en début de semaine. De manière générale, la visibilité horizontale est meilleure le lundi que les jours suivants. En raison du temps nécessaire à la formation des poussières fines secondaires, l'amélioration des valeurs observées le week-end entraîne une charge en poussières fines plus faible le lundi.

La Suisse et les pays voisins ont pris de nombreuses mesures pour réduire les émissions de polluants atmosphériques afin de préserver la santé de l'être humain et l'environnement. Ces mesures ont contribué à une nette amélioration de la qualité de l'air et ont eu des répercussions positives sur la visibilité en Suisse.

1 Introduction

1.1 Horizontal visibility

Horizontal visibility refers to how clear the atmosphere is and how easily distant objects can be resolved.[1] The Koschmieder equation or formula is often used to define visibility mathematically (Equation 1).

$$V = \frac{-ln(C_L)}{\beta_e} \tag{1}$$

In Equation 1, visibility (V) is inversely related to the atmospheric extinction coefficient (β_e) which is defined as the amount of light which is redirected from its original path.[1] C_L is generally set at 2 % (0.02) and is a contrast threshold coefficient derived from an average person's ability to resolve contrasting objects. This results in Equation 1 usually taking the form of $V = 3.912/\beta_e$. It is generally acknowledged that the Koschmieder Equation 1 is too simple of a model to describe atmospheric visibility in the real-world,[2,3] however, it is a useful empirical model nonetheless.

The total extinction coefficient β_e can be expressed as the sum of scattering by particles and gases ($\beta_{s,p}$ and $\beta_{s,g}$ respectively) and absorption by particles and gases ($\beta_{a,p}$ and $\beta_{a,g}$ respectively; Equation 2):

$$\beta_e = \beta_{s,p} + \beta_{s,g} + \beta_{a,p} + \beta_{a,g} \tag{2}$$

In non-pristine environments, light scattering and attenuation are dominated by particulate matter (PM), and the influence from gases on the total extinction coefficient (β_e) is small.[4] Gases scatter light via Raleigh scattering and the effect on visibility is smaller than light scattering by particles via Mie scattering.[5]

Nitrogen dioxide (NO_2) is the only gas which is present at appropriate concentrations that can lead to significant absorption of visible light. At Heathrow airport in London (UK) it was found that the light absorption of NO_2 contributes 3–5 % to the total extinction coefficient.[4] For most sites in Switzerland the contribution from light absorption of NO_2 to the total extinction would be lower than the values reported for Heathrow airport due to lower mean concentrations. Finally, the extinction efficiency of particles is dominated by light scattering. The single scattering albedo (SSA) of atmospheric particles is defined as the ratio of total scattering efficiency to total extinction efficiency. The SSA of atmospheric particles is typically > 0.9, meaning that the scattering efficiency of particles is about ten times larger than the absorption efficiency.[6]

The SSA is typically determined for dry particles. However, PM typically contains nitrate, sulfate and other hygroscopic compounds. Depending on the RH, PM can therefore absorb water and the particles grow in size leading to an increasing ability to scatter light. Consequently, the scattering coefficient depends on RH, *i.e.*, $\beta_{s,p}(RH)$. The enhancement of the scattering coefficient compared to dry conditions $\beta_{s,p}(dry)$ can be described by Equation 3:

$$\beta_{s,p}(RH)/\beta_{s,p}(dry) = (1 - RH/100)^{-\gamma} \quad (3)$$

with γ the hygroscopicity parameter (Figure 1). The above considerations lead to the expectation where if atmospheric PM concentrations decrease, visibility increases.

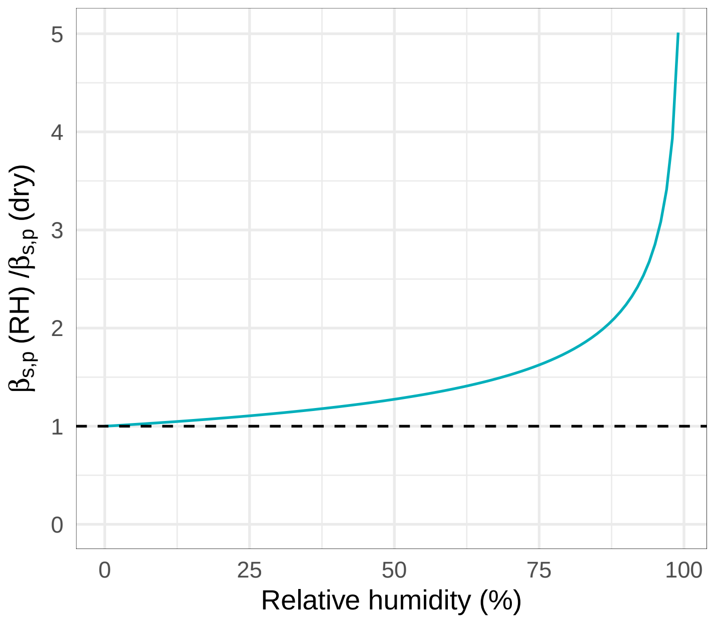

Figure 1: Schematic representation of the enhancement of the scattering coefficient at varying relative humidity compared to dry conditions (Equation 3 with $\gamma = 0.35$).

1.2 Switzerland's air quality trends

Across Switzerland, PM concentrations have decreased over the last few decades.[7–10] The associated improvement in air quality is certainly a consequence of the implemented policies for the abatement of atmospheric emissions. The decreases in PM concentrations are occurring at different rates in different locations and environments, but isolated rural mountain locations are also demonstrating significant decreases in concentrations. Therefore, not only are local emissions of PM decreasing, as are emissions and the generation of PM precursors in surrounding European locations. The relationship between PM concentrations and visibility results in an expectation that horizontal visibility and visual range should have increased over the last three decades across most of Switzerland.

1.3 Objectives

The primary objective of this report is a descriptive-based analysis for horizontal visibility observations across Switzerland which have been recorded between 1980 and 2018. A "high-level" approach will be taken and ambient PM measurements will be integrated to demonstrate the linkage between visibly and air quality. This report extends a previous feasibility study conducted by Meteotest [11], and has been written to document what data are available and evaluate the potential of a more in-depth analysis.

2 Methods

2.1 Data

2.1.1 Horizontal visibility

Horizontal visibility observations for 25 sites were supplied by Switzerland's Federal Office of Meteorology and Climatology (MeteoSwiss) via an official data request§. Observations were available between 1980 and 2018 – a monitoring period of 38 years. The visibility data were supplied in their coded form which is used for data entry by the personnel at the observing sites. The coding system used was the SYNOP VV "horizontal visibility at surface" system which has a maximum resolution of 100 m.[12] The visibility observations were decoded into metres and this unit was used for the analysis.

Visibility observations in Switzerland are reported primarily for broad weather descriptions or classification, aviation obligations, and for auxiliary information. Therefore, the time series which are produced are not collected with the intention of long-term trend analyses which is what is reported in this document. This limitation should be accepted, but has been managed for the data analysis conducted here.

The coded observations are produced and recorded by human observers and are therefore subjective measurements. A standard procedure is followed where an observer determines the furthest distance object which can be resolved. Generally, strongly contrasting landmarks such as mountains, churches, and other buildings are identified and their distance is known from the observing site.[13]

The subjective nature of the visibility observations make the presence of long term, uninterrupted time series somewhat uncommon and unrealistic. Such observations frequently contain discontinuities where the visibly values shift due to different human operators, site relocations, changes in observing time, and the introduction of automated visibility sensors which "suggest" a value to the operators. If these processes influence the time series greatly, it is often not suitable to conduct a trend analysis.

To identify what sites' time series were suitable for trend analysis, the visibility observations were exposed to the adaptive Kolmogorov-Zurbenko low-pass filter (KZA filter).[14] The KZA filter identifies abrupt changes in time series, but maintains changes which occur slowly in time. The KZA filter's parameters were 365 and 3 for the window-size and number of iterations respectively. These KZA filtered time series were used to visually determine what sites had significant discontinuities. Examples of a good, mostly continuous time series with a com-

§Datenanfrage/INC000002280459, Daniel Müller, October 2019 parison to one which contains a significant shift is shown in Figure 2 and all sites' KZA filtered observations are shown in Figure SI 1. Eleven sites were kept for analysis from the total of 25 (Table 1). A map of the 11 sites is available in Figure 3. The 11 sites covered a range of different environments including mountain observing platforms, international airports, suburban areas, and rural areas in the Swiss plateau.

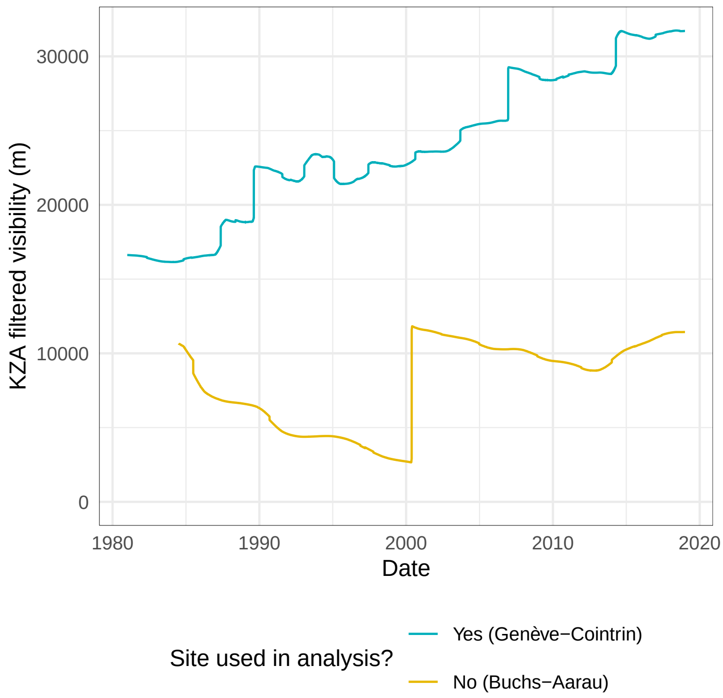

Figure 2: KZA filtered visibility time series for two sites, one site which was used for the data analysis (Genève-Cointrin) while the other contains a significant discontinuity and was not used in the analysis (Buchs-Aarau).

Adjustment of some of the heterogeneous time series, especially those around Bern, an area with poor representation with the 11 sites with "good" time series was attempted. Offsets were applied (based on the KZA filter outputs) but the time series' distributions were very different and a simple conditional offset was inadequate to homogenise the time series for these sites (an example for Buchs-Aarau is shown in Figure SI 2). Further techniques may be suitable to recover such time series, but further investigation was not done for this analysis.

2.1.2 Other observations

Hourly surface-based meteorological observations were also supplied by MeteoSwiss[§] for the same time period where visibility observations were available (between 1980 and 2018). Switzerland's PM_{10} and $PM_{2.5}$ observations were also used and were gained from **smonitor** Europe,

[§]Rolf Bleiker, MeteoSwiss, November 2019

Table 1: Location details about the 11 Swiss visibility observing sites used for the data analysis.

Site	Site name	Site area	Canton	Lat.	Long.	Elevation (m)
ALT	Altdorf		Uri	46.887	8.622	438
BAS	Basel-Binningen		Basel Landschaft	47.541	7.583	316
GSB	Col du Grand St-Bernard		Valais	45.869	7.171	2472
GVE	Genève-Cointrin	Airport	Geneva	46.248	6.128	411
JUN	Jungfraujoch	Alpine Col	Valais	46.547	7.985	3580
KLO	Zürich-Kloten	Airport	Zürich	47.480	8.536	426
MER	Meiringen		Bern	46.732	8.169	589
OTL	Locarno-Monti		Ticino	46.172	8.788	367
PAY	Payerne		Vaud	46.812	6.942	490
SAM	Samedan	Airport	Graubünden	46.526	9.879	1709
SMA	Zürich-Fluntern	Suburban	Zürich	47.378	8.566	556

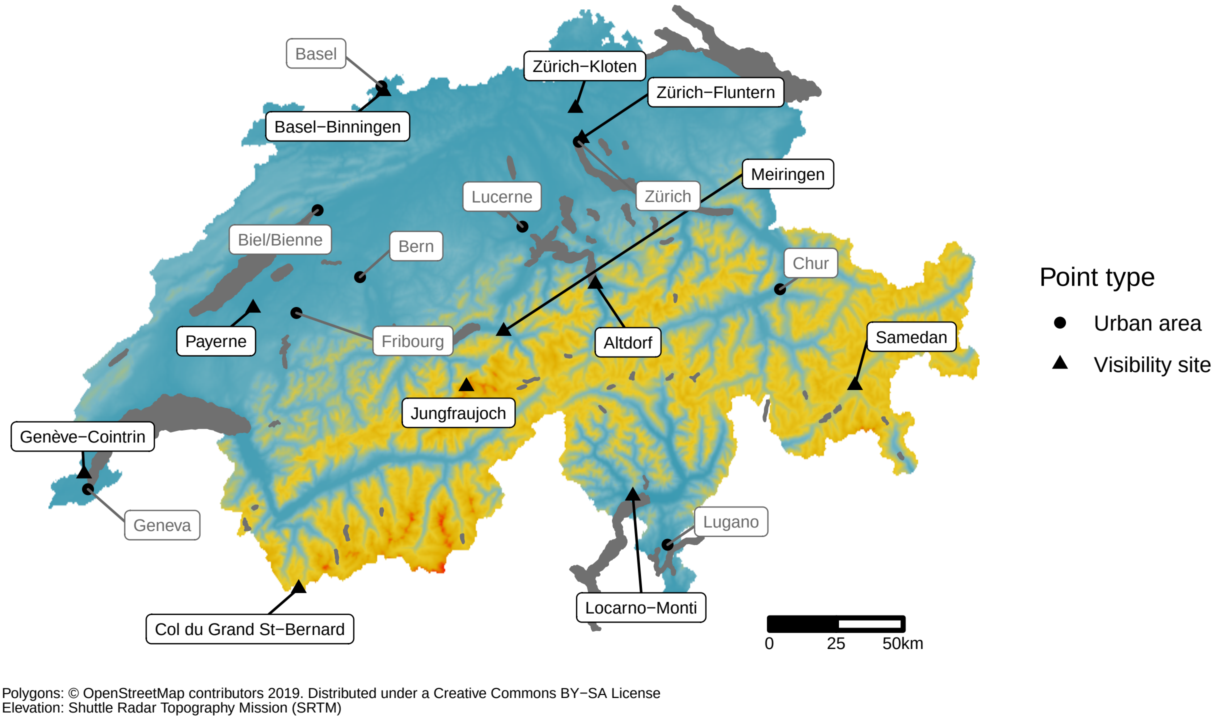

Figure 3: Switzerland's 11 horizontal visibility monitoring sites used for this analysis and some urban areas for orientation. The colours indicate the elevation of the terrain and filled dark grey areas show larger lakes and reservoirs. For additional location details, see Table 1.

a database containing data sourced from the data repositories of the European Environmental Agency (Airbase and Air Quality e-reporting; AQER), thus, validated European air quality monitoring data for the analysis period.[15–17] Daily PM_{10} and $PM_{2.5}$ observations (almost always sampled with high volume samplers) were used in the analysis because these time series started much earlier (from about 1997 onwards) compared to the the hourly time series. Therefore, the visibility and meteorological observations were aggregated to daily means when being used alongside the PM data. Sulfate observations were available for Payerne and Jungfraujoch and unlike the other "routine" air quality monitoring data, these data were retrieved from the air quality monitoring network's database (the National Air Pollution Monitoring Network, NABEL).[18]

The visibility and surface meteorological observations were taken at the same facility (site). However, the air quality monitoring sites are disconnected, operated by separate parties, and form a different monitoring network. Nearby, representative air quality monitoring sites were matched to six visibility sites and analysed together. The linkage between the meteorological and air quality sites are displayed in Table 2.

Table 2: The visibility sites (vis.) and their linkage to air quality monitoring sites (AQ) when available.

Site name (vis.)	Site (AQ)	Site name (AQ)	Local ID (AQ)	Lat. (AQ)	Long. (AQ)	Elev. (AQ; m)	Area (AQ)
Basel-Binningen	ch0008a	Basel-Binningen	BAS	47.541	7.583	316	Suburban
Genève-Cointrin	ch0050a	Meyrin-Vaudagne	MEY	46.231	6.074	439	Suburban
Jungfraujoch	ch0001g	Jungfraujoch	JUN	46.547	7.985	3578	Rural
Zürich-Kloten	ch0005a	Dübendorf-EMPA	DUE	47.403	8.613	432	Suburban
Payerne	ch0002r	Payerne	PAY	46.813	6.944	489	Rural
Zürich-Fluntern	ch0010a	Zürich-Kaserne	ZUE	47.378	8.530	409	Urban

2.2 Trend analysis

Trend analysis was preformed with the robust, non-parametric Theil-Sen slope estimator.[19] The interface to this estimator was provided by the **saqtrendr** R package.[20] In preparation for the trend test, observations which were reported at higher resolution than monthly were aggregated to monthly means and exposed to classical seasonal decomposition by loess. Annual means and counts were not decomposed. All tests were preformed at the $\alpha = 0.05$ significance level.

3 Results and discussion

3.1 Visibility distributions

The distributions of visibility observations in Figure 4 show that the number of higher visibility observations increased for most monitoring sites during the 1980 to 2018 monitoring period. This feature can be identified by the distributions progressively shifting right in the more recent five-year blocks. This rightward shift in the visibility observations' distributions was not present for Col du Grand St-Bernard and Jungfraujoch which are both elevated, mountainous monitoring sites (Table 1). The visibility distributions for these two alpine sites show that conditions were either "clear", or "not-clear", with fewer observations between these extremes. This is expected because their location and surrounds are distinct from the other, lower altitude sites included in the analysis.

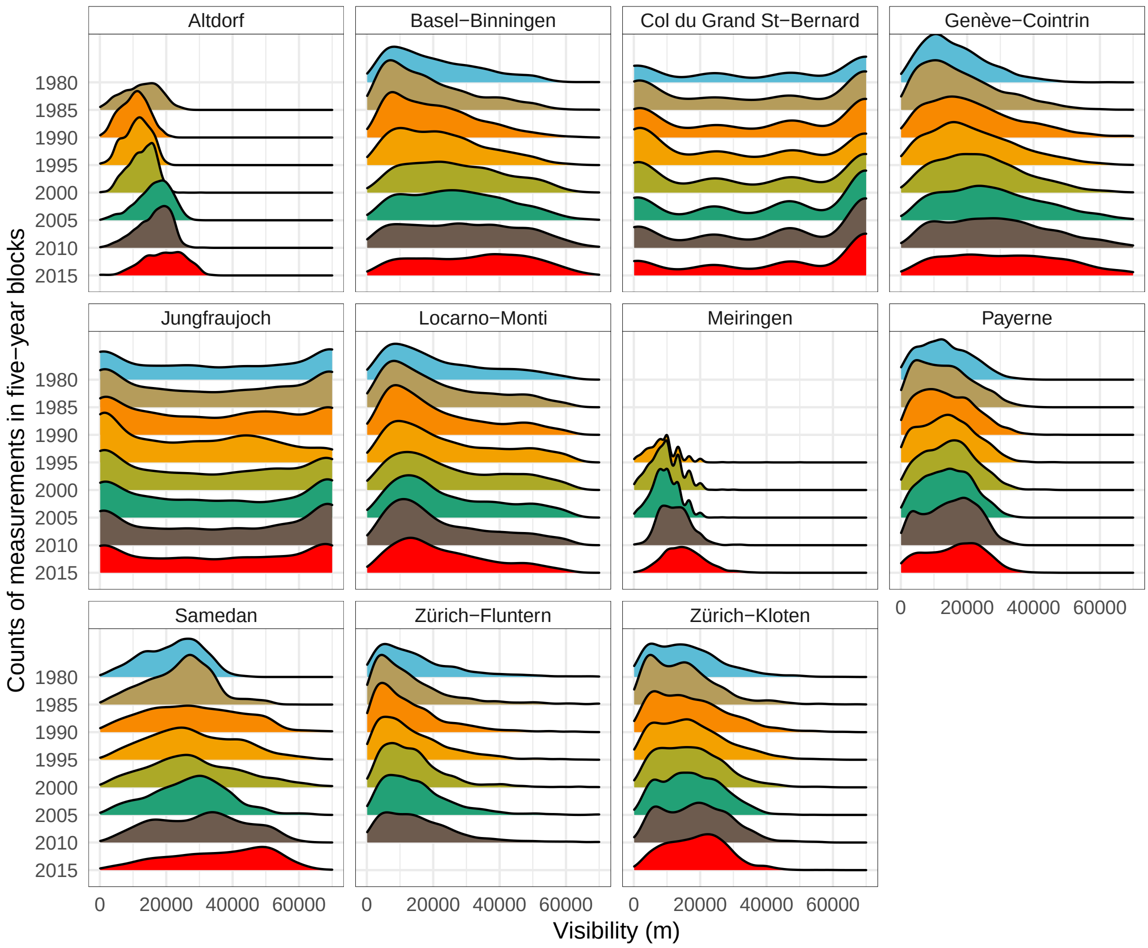

Figure 4: Distributions of visibility observations in five-year blocks between 1980 and 2018 for 11 visibility monitoring sites in Switzerland.

3.2 Mean visibility

When the visibility time series for the 11 monitoring sites are plotted, many locations showed progressively increasing visibility between 1980 and 2018 (monthly means shown in Figure 5). Basel-Binningen and Genève-Cointrin show the clearest increase during the monitoring period while Payerne and the two sites in Zürich (Zürich-Fluntern and Zürich-Kloten), seem more stable. It is interesting to note that the mean visibility in Payerne and the two sites in Zürich are clearly lower than in Basel-Binningen, Genève-Cointrin and Locarno-Monti (see also Figure 4). The lower mean visibility in Payerne and the two sites in Zurich compared particularly to the two other sites north of the Alps (Basel-Binningen, Genève-Cointrin) is surprising – all these sites are not located in the immediate vicinity of significant sources of PM such as road traffic and the spatial distribution of atmospheric PM is rather homogeneous. As shown in a recent publication[9], the absolute level as well as the temporal changes of PM_{10} is similar in sites on the Swiss Plateau that are not strongly impacted by nearby road traffic emissions. Moreover, the visibility in Payerne and the two sites in Zurich are not constrained by topography, the reason for the lower visibility at these sites remains therefore unknown. In contrast, the lower mean visibility in Altdorf and Meiringen might be explained by their location in valleys and possible topographic confinement (see Section 3.3).

3.3 Seasonal patterns

When the visibility observations are aggregated by season, a clear distinction between the mountainous locations and other sites was observed. The two alpine sites, Col du Grand St-Bernard and Jungfraujoch as well as Samedan, a valley site which is located at altitude (1709 m), had the best visibility across all seasons while the sites located in central Switzerland, Meiringen and Altdorf had the lowest visibility on average (Figure 6). Both the Meiringen and Altdorf sites are located in valleys, and their low average visibility may simply be a result of topographic confinement where the maximum visual range is constrained by surrounding mountains.

For the non-alpine sites, summer was generally the season with the best visibility while winter experienced the worst (Figure 6). However, Locarno-Monti did not show this pattern and the seasonal means were tightly clustered together, which may indicate the processes which drive seasonal visibility patterns south of the Alps are different than those experienced elsewhere in Switzerland.

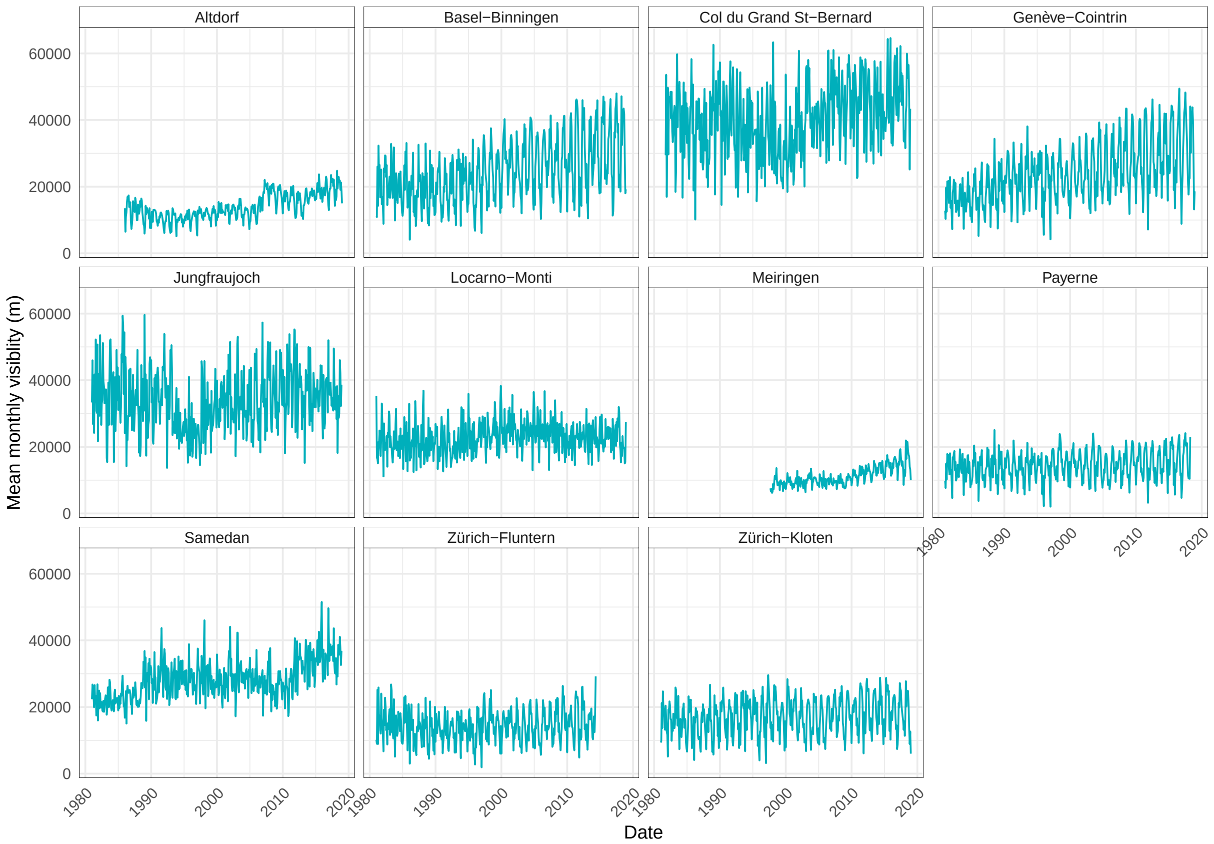

Figure 5: Mean monthly visibility time series between 1980 and 2018 for 11 visibility monitoring sites in Switzerland.

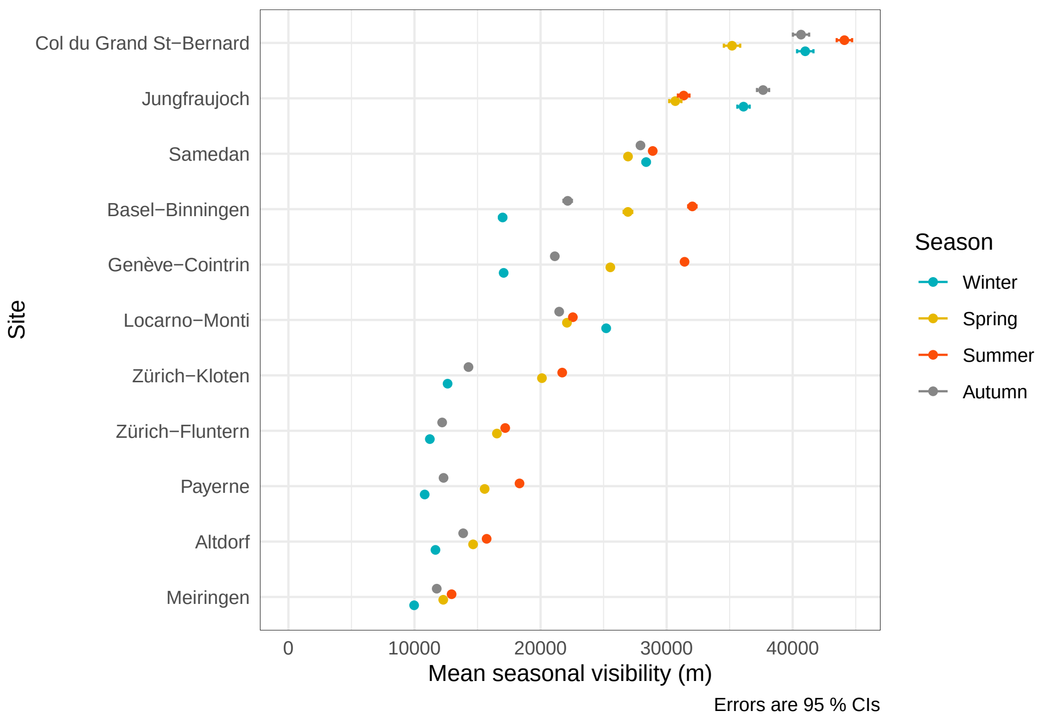

Figure 6: Mean seasonal visibility between 1980 and 2018 for 11 visibility monitoring sites in Switzerland. Sites are ordered by their overall mean visibility.

3.4 Weekday patterns

For the majority of monitoring sites, the best visibility conditions were found, on average on Sundays (Figure 7). For many locations, Mondays were also days with high average visibility. Average weather conditions will not be different for any given day of the week, and therefore, these patterns must be driven by emissions of PM. Interestingly, the observation that Mondays often experience good visibility suggests that there is a lag between the lower rates of emissions during the weekend (Saturday and Sunday) and their influence on atmospheric visibility. Similar time lags and day-to-day carryover on concentrations have been described for ozone and PM.[7,21] The atmospheric formation of ozone and the secondary PM fraction requires time so that the lower emissions of precursors during the weekend leads on average to lower ambient concentrations in the beginning of the week. The observed weekday pattern at the low altitude sites demonstrates the importance of the PM concentration for the horizontal visibility.

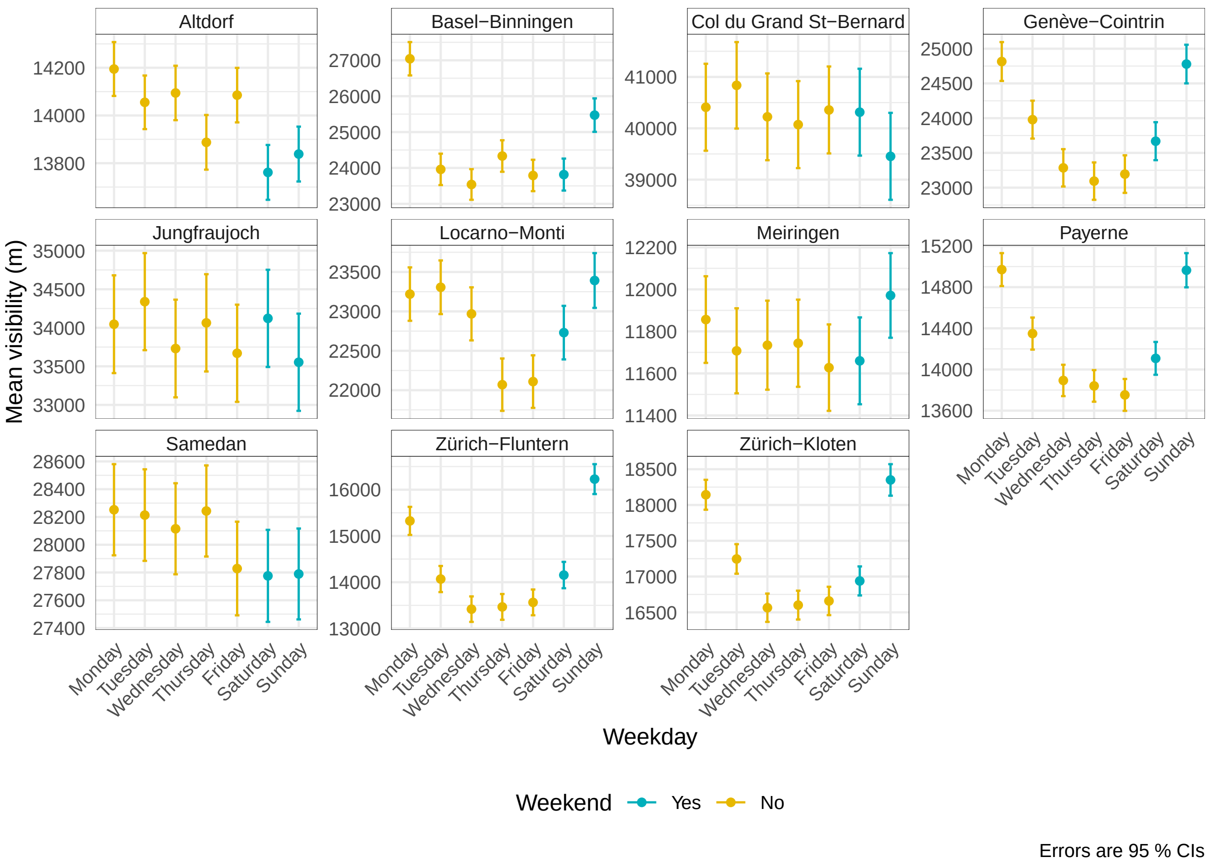

Figure 7: Mean weekday visibility between 1980 and 2018 for 11 visibility monitoring sites in Switzerland.

3.5 Time of day patterns

The monitoring procedure generally resulted in visibility measures being reported at three-hour intervals at the visibility monitoring sites. The different observing times throughout the

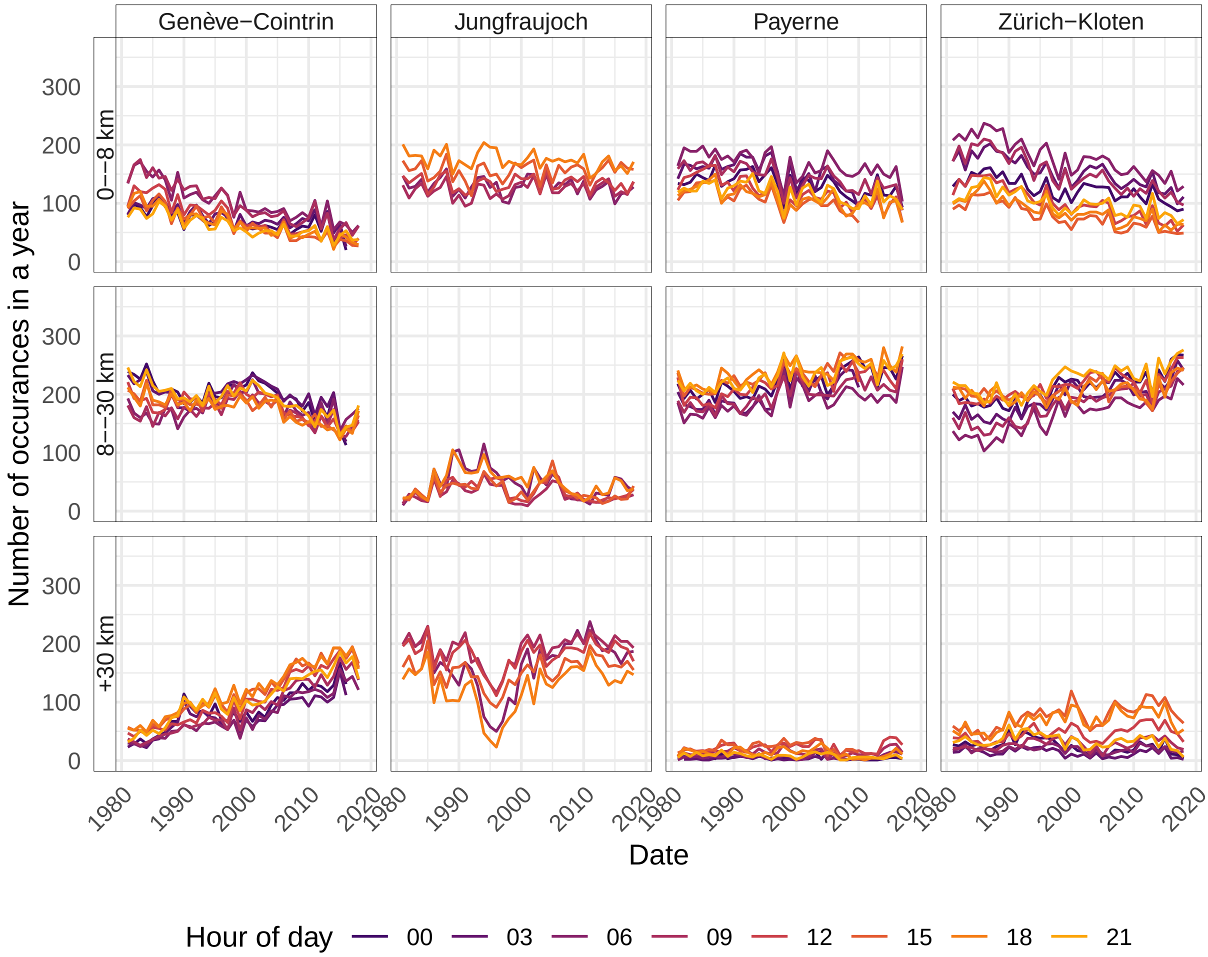

Figure 8: Counts of three visibility classes at different hours of the day for four selected visibility monitoring sites in Switzerland between 1980 and 2018.

day show good consistency for most monitoring sites (four sites shown in Figure 8).

Figure 8 also splits visibility into three broad visibility classes: 0–8 km, 8–30 km, and ≥30 km. It is very clear for sites which have experienced improvements in visibility between 1980 and 2018 that the number of "good" visibility days have increased at the expense of the days with poor visibility across all times of the day. Figure 8 shows *occurrences*, and therefore the occurrences of poor visibility conditions have decreased while occurrences of very good conditions have increased. The observed changes in the occurrence of poor visibility conditions is in agreement with a recent study by MeteoSwiss, where a decreasing frequency of the occurrence of fog and low stratus (FLS) events has been found for the period 1957–2016.[22]

3.6 Trend analysis

To formally evaluate the features seen in Figure 5 and Figure 8, formal trend analysis of mean visibility, low visibility conditions, and extremely good visibility conditions was conducted. Mean visibility was found to be significantly increasing at 10 of the 11 monitoring sites (Figure 9 and Table 3). The maximum increase was 440 m y^{-1} or 4400 m decade^{-1} at Genève-Cointrin while Locarno-Monti experienced the slowest rate of visibility increase at 64 m y^{-1}. Jungfraujoch's visibility had not changed significantly over time. Jungfraujoch's visibility also shows an upward trend, although the calculated change over time is not significant at 95 % confidence.

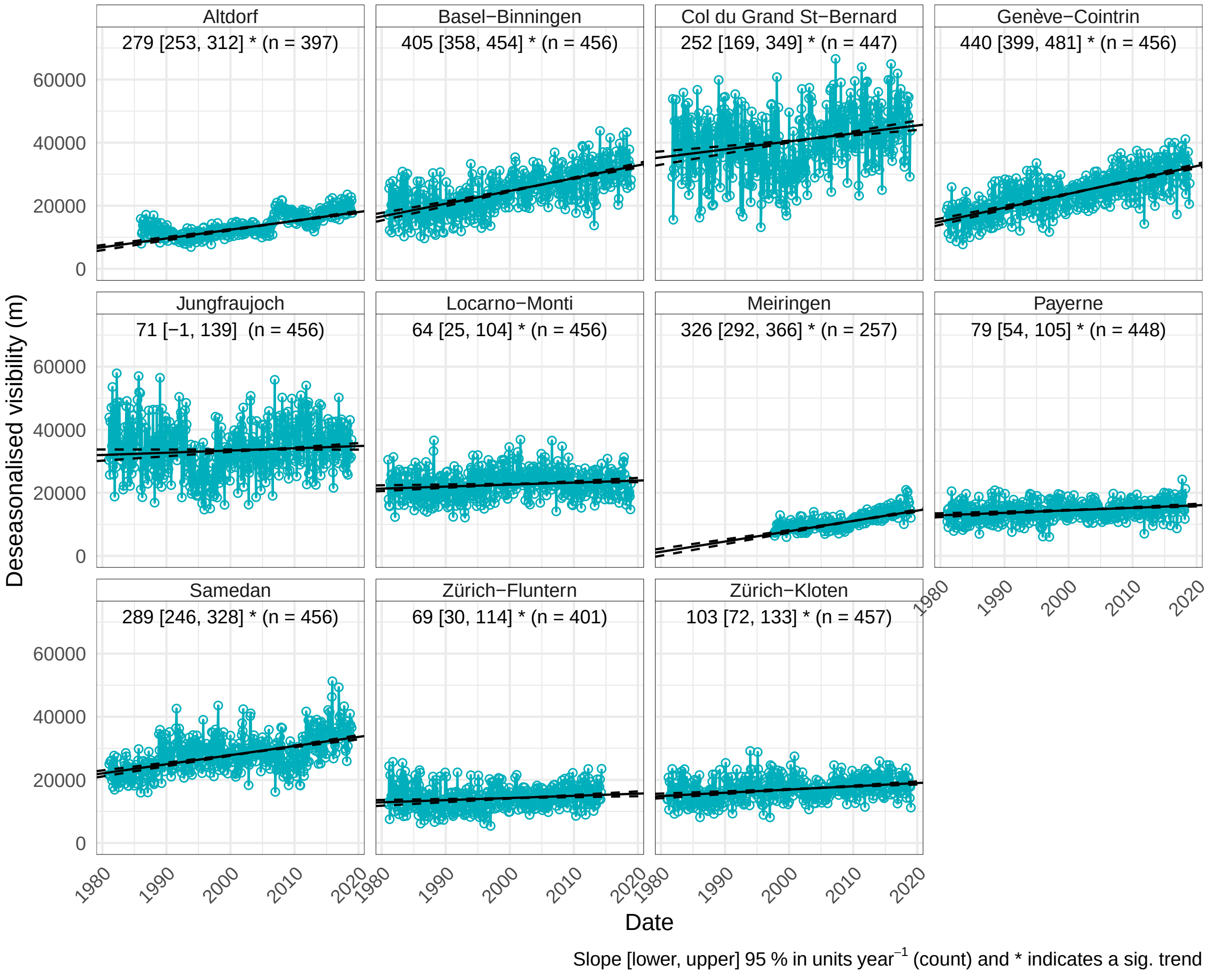

Figure 9: Deseasonalised monthly mean visibility trends for 11 visibility monitoring sites in Switzerland. The units in the annotations are m y^{-1}.

Table 3: Results of trend tests for 11 visibility sites in Switzerland between 1980 and 2018 arranged by rate of change.

Site	Site name	Start date	End date	n	p-value	Sig. trend	Slope (m y^{-1})	Slope (m decade^{-1})
GVE	Genève-Cointrin	1981-01-01	2018-12-01	456	< 0.01	Yes	440	4400
BAS	Basel-Binningen	1981-01-01	2018-12-01	456	< 0.01	Yes	405	4050
MER	Meiringen	1995-01-01	2019-01-01	257	< 0.01	Yes	326	3260
SAM	Samedan	1981-01-01	2018-12-01	456	< 0.01	Yes	289	2890
ALT	Altdorf	1981-01-01	2019-01-01	397	< 0.01	Yes	279	2790
GSB	Col du Grand St-Bernard	1981-10-01	2018-12-01	447	< 0.01	Yes	252	2520
KLO	Zürich-Kloten	1981-01-01	2019-01-01	457	< 0.01	Yes	103	1030
PAY	Payerne	1981-01-01	2018-04-01	448	< 0.01	Yes	79	790
JUN	Jungfraujoch	1981-01-01	2018-12-01	456	0.057	No	71	710
SMA	Zürich-Fluntern	1981-01-01	2014-05-01	401	< 0.01	Yes	69	690
OTL	Locarno-Monti	1981-01-01	2018-12-01	456	< 0.01	Yes	64	640

3.6.1 Low visibility occurrences

The occurrence of low visibility conditions is of general interest because they are the conditions which can be disruptive for recreational and economic activities.[22,23] Such conditions may also indicate polluted conditions which are relevant for health effects. What is considered low visibility conditions is very much a subjective measure, but here we use less than 5000 m as in Vautard et al. [24]. The trends of low visibility conditions are shown in Figure 10 and the units of the annotations are in days per year ($d\,y^{-1}$). All sites but Jungfraujoch demonstrated significant decreases of low visibility conditions during the monitoring period and ranged from 3.9 $d\,y^{-1}$ (at Altdorf) to 0.6 $d\,y^{-1}$ (at Payerne).

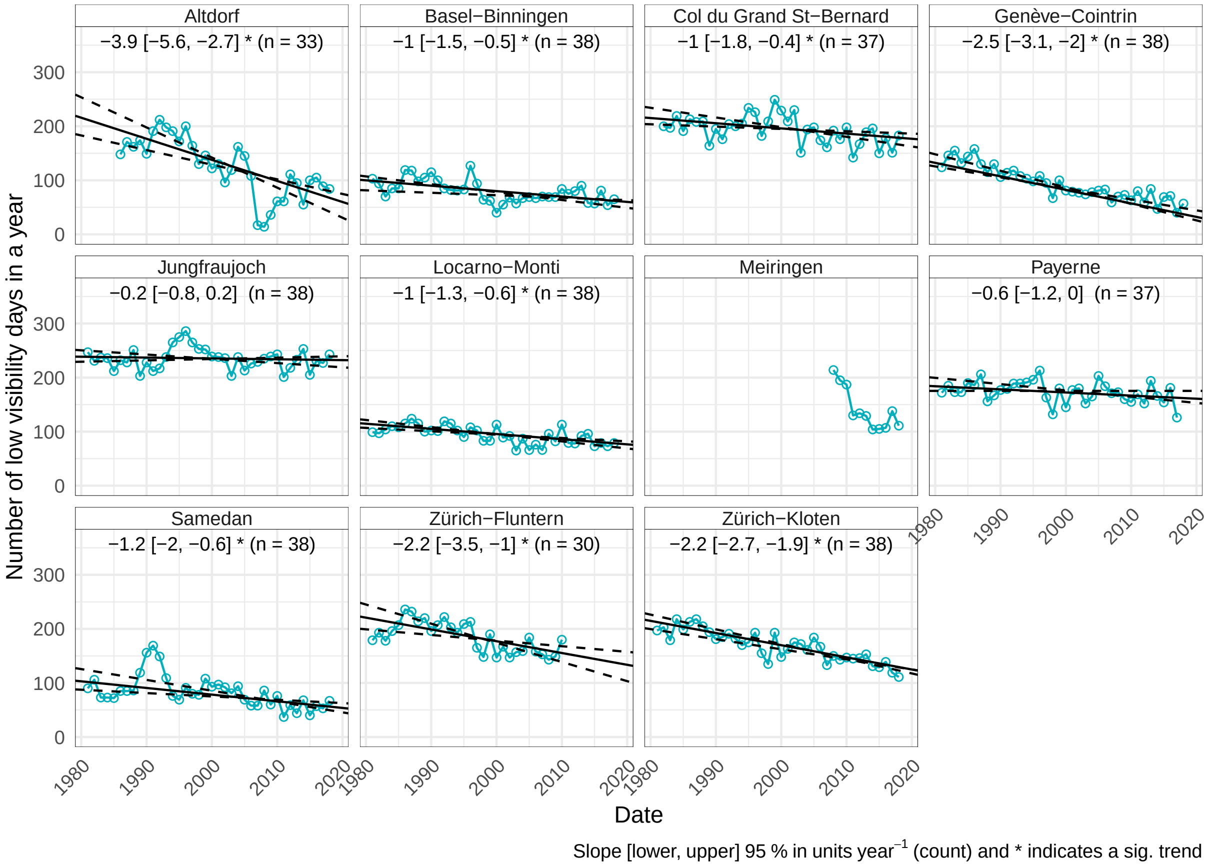

Figure 10: Number of low visibility days per year for 11 sites in Switzerland between 1980 and 2018. Low visibility was defined as ≤ 5000 metres. Meiringen's trends are not displayed due to a short time series.

3.6.2 Extremely clear occurrences

Extremely good visibility or very clear conditions is also a subjective measure like poor visibility. Here, we have defined extremely clear conditions as ≥ 30 km and the occurrence have increased significantly between 1980 and 2018 for many locations in Switzerland (Figure 11).

Basel-Binningen showed the greatest increasing rate of 4.4 $d\,y^{-1}$. Altdorf was not included in the trend analysis due to an inappropriate time series, but the data show that in this location, extremely clear conditions were not experienced before 2005, but have became more frequent in later years. Again, the reason for the absence of extremely clear observations in Altdorf could be due to the possible topographic confinement. The obtained trends of extremely clear occurrences require careful interpretation. The subjective nature of the visibility observations as described in Section 2.1.1 may be especially relevant for extremely clear conditions.

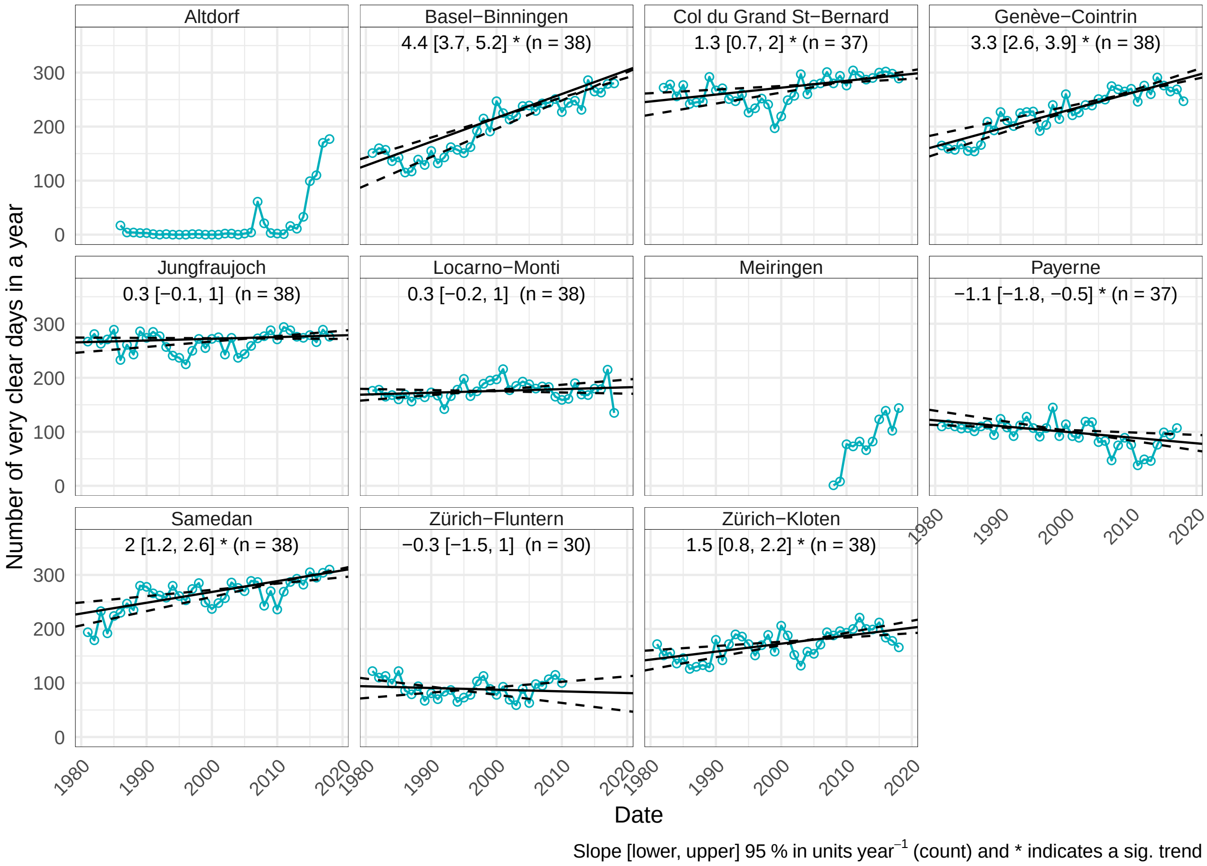

Figure 11: Number of extremely clear days per year for 11 sites in Switzerland between 1980 and 2018. Extremely clear conditions were defined as ≥ 30 km. Altdorf and Meiringen's trends are not displayed due to a short, or non-monotonic time series.

3.7 Relative humidity

Relative humidity (RH) is known to be a key driver of horizontal visibility.[1,25] Across Switzerland, visibility was negatively correlated with RH with very high RH conditions (98–100 %) resulting in very low visibility (Figure 12). Such high RH conditions would be associated with fog events.

When the visibility and relative humidity dependencies are explored by decade as in Singh et al. [4], most monitoring sites have experienced improved visibility across all relative humid-

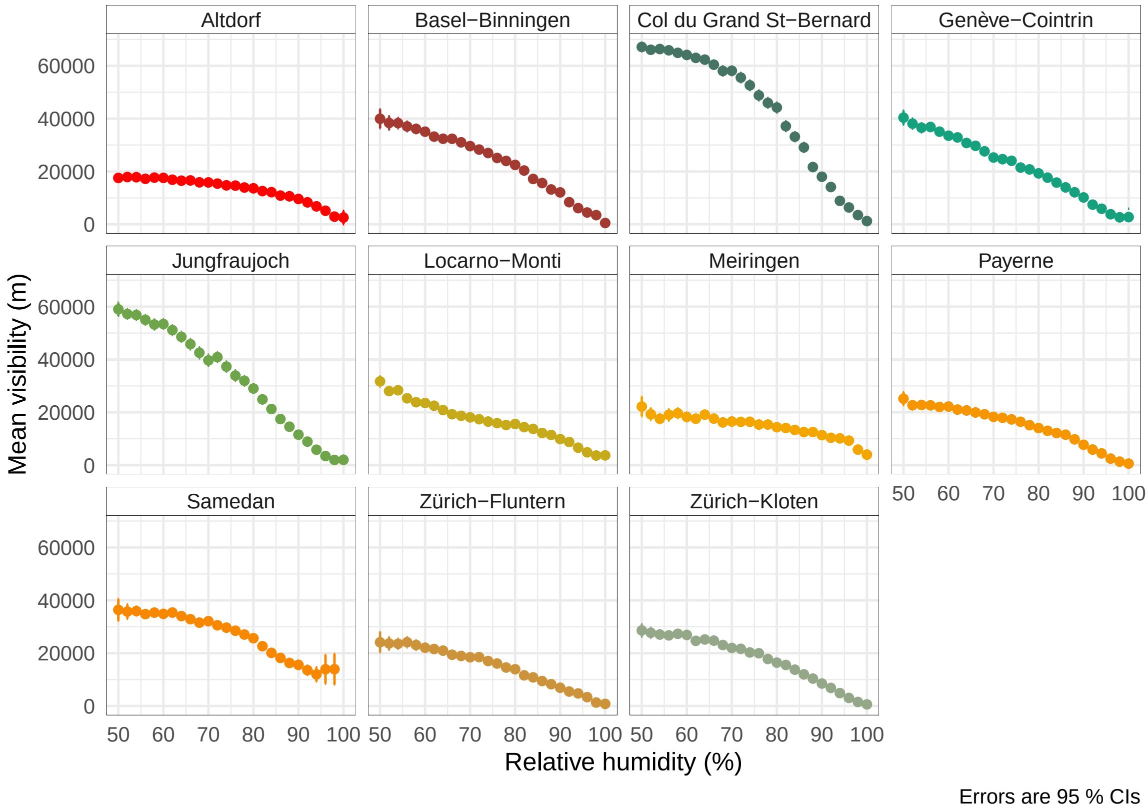

Figure 12: Visibility dependence on relative humidity (RH) for 11 sites in Switzerland. RH has been rounded to whole numbers before aggregation.

ity conditions in the more recent decades (Figure 13). This increase over the decades is clearest in Basel-Binningen and Genève-Cointrin. The observed increase in horizontal visibility at low relative humidity conditions can certainly be attributed to the improvements in air quality (in particular PM) during the past decades (see Section 1.1).

3.8 Particulate matter concentrations

Visibility was found to be negatively correlated with local ambient PM_{10} concentrations in a non-linear fashion (Figure 14). Interestingly, for all sites but Jungfraujoch, the highest mean visibility were experienced, not at the lowest concentrations of PM_{10}, but at about 10 $\mu g\,m^{-3}$ which resulted in a distinctive "bump"-pattern in the visibility-PM_{10} dependency plots. The reduction of visibility at the lowest PM_{10} concentration may be driven by wet conditions where rainfall removes PM from the atmosphere but visibility is low.

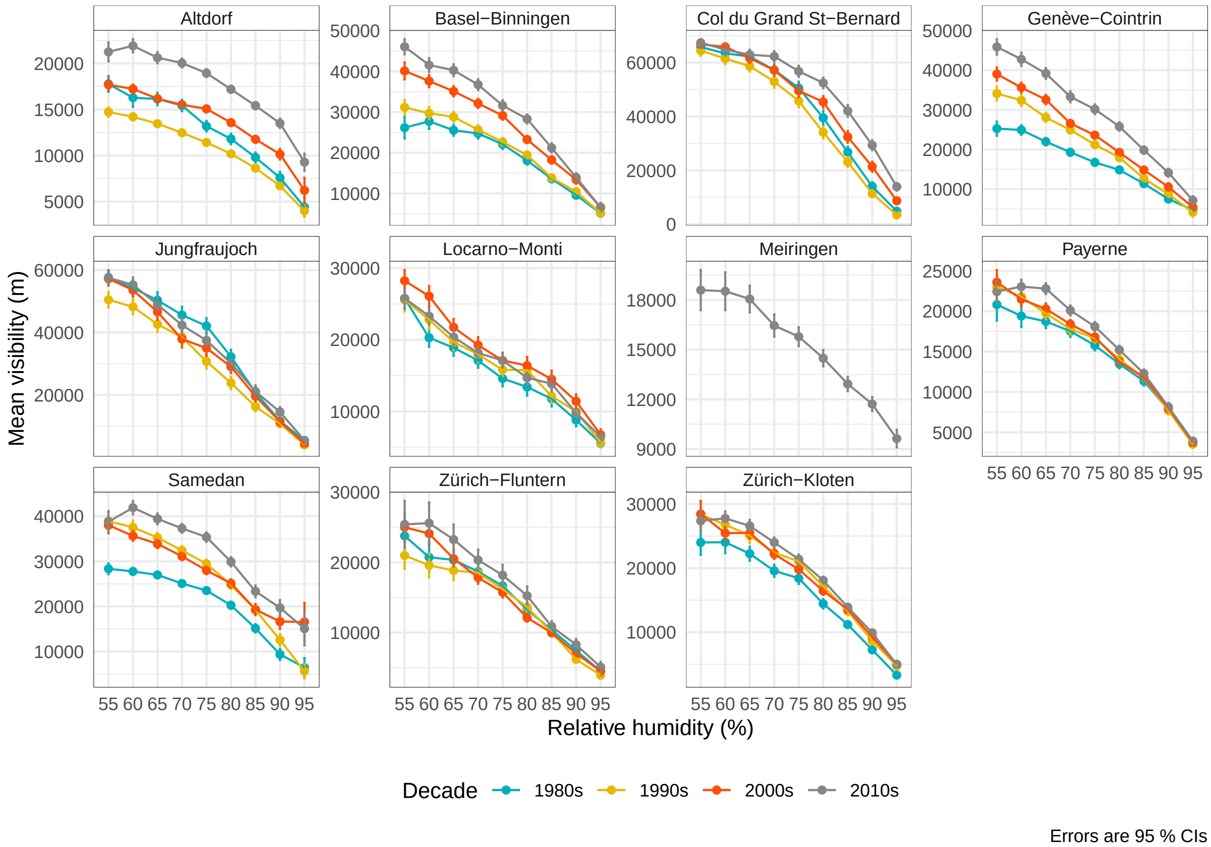

Figure 13: Visibility dependence on relative humidity (RH; between 55 and 95 %) for 11 sites in Switzerland grouped by decade. RH has been rounded to the nearest 5 %. Meiringen's RH observational record started in the 2010s and therefore has fewer decades plotted.

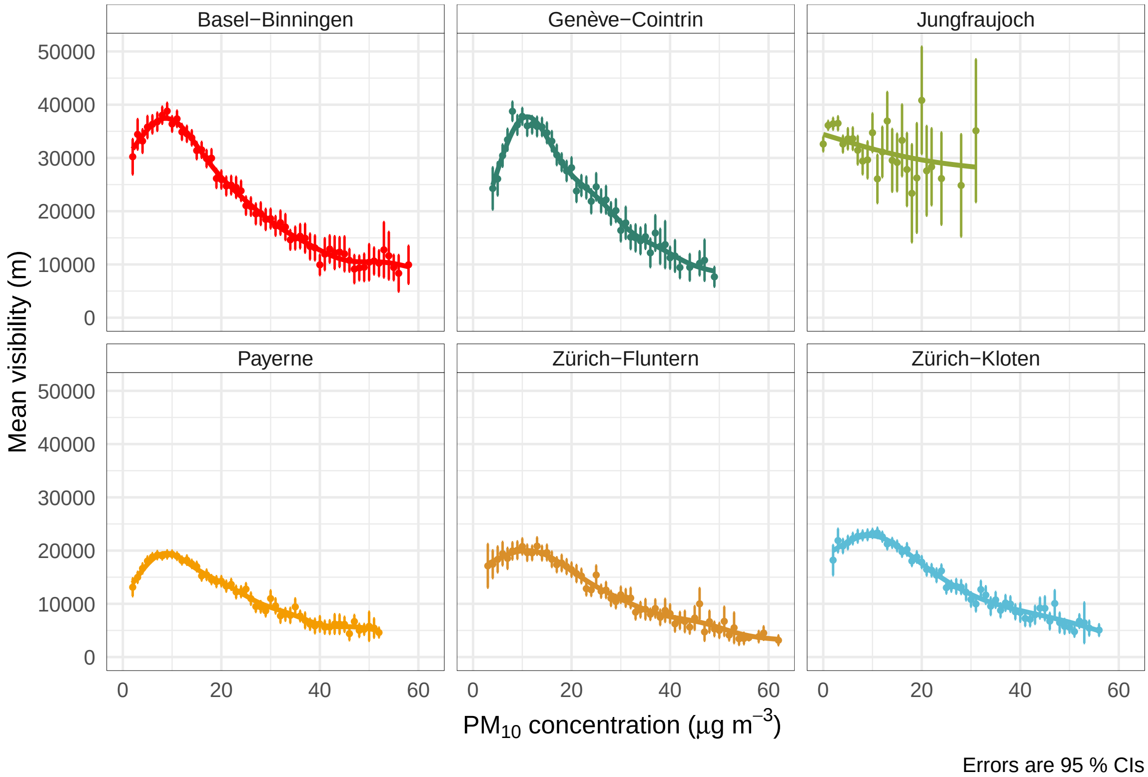

Figure 14: Visibility dependence on ambient PM_{10} concentrations. PM_{10} has been rounded to whole numbers for aggregation.

When visibility and PM (PM_{10}, $PM_{2.5}$, and sulfate) trend components are normalised, the two variables show clear divergence over time (K-Z trends shown in Figure 15). Based on the simple relationship between visibility and PM concentrations discussed in Section 1, PM concentration reduction would have been a principal driver in the improvement in visibility in Switzerland. Formalising this relationship has not yet been attempted.

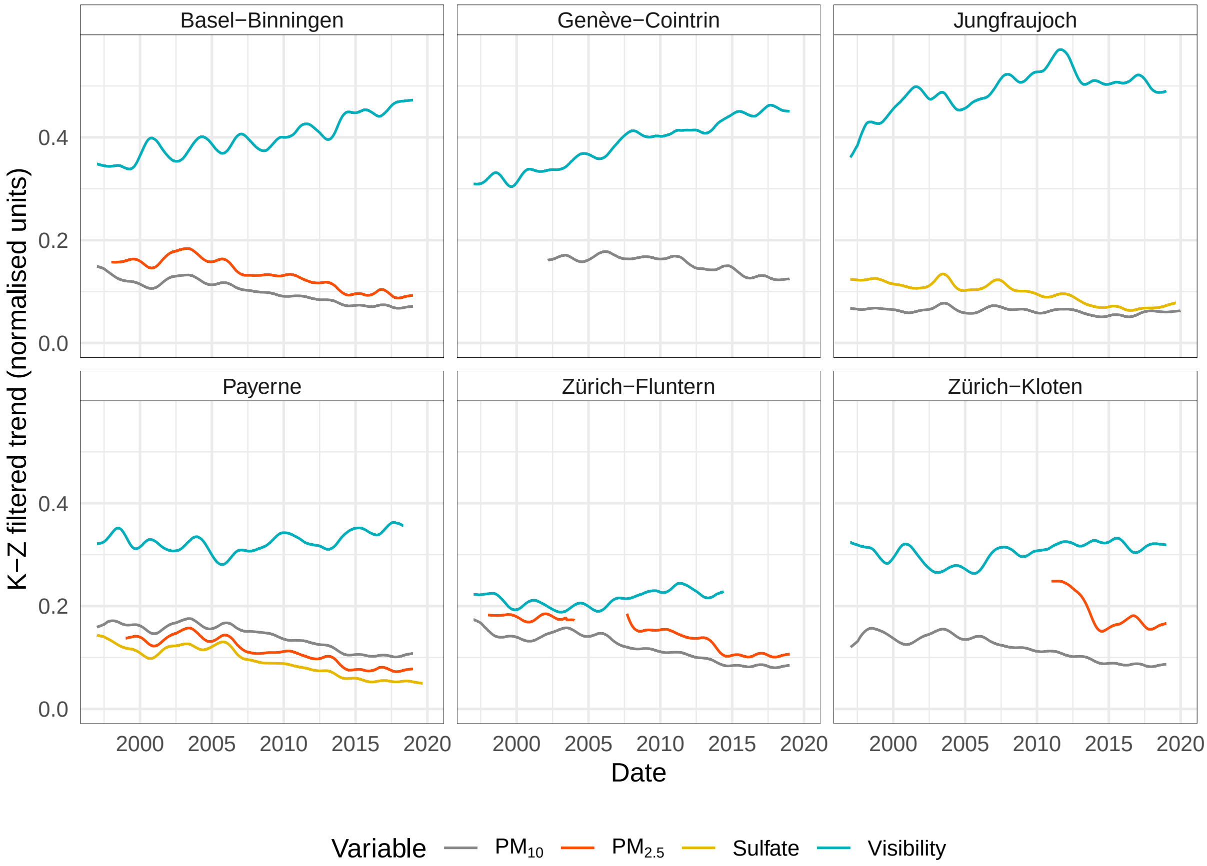

Figure 15: Normalised K-Z filtered trends of horizontal visibility and ambient PM_{10}, $PM_{2.5}$, and sulfate (at Payerne only) concentrations between 1997 and 2018 for six sites in Switzerland.

4 Conclusions

Horizontal visibility primarily depends on ambient PM concentrations and the effect of RH on the scattering efficiency of PM. As a result of policies for the abatement of emissions that have been implemented during the past decades in Switzerland and the neighbouring countries, PM concentrations have, and are, decreasing over time. Thus, improvements in horizontal visibility are to be expected.

To test this, horizontal visibility observations between 1980 and 2018 for 11 sites across Switzerland were analysed alongside surface meteorological and ambient air quality data. It should be emphasised that the available horizontal visibility observations have not been collected with the intention of long-term trend analyses and data quality is an important factor for this study. In particular, it was necessary to identify and exclude time series that were not appropriate for the intended analyses due to discontinuities and inhomogeneities that are difficult to correct. As a consequence, the spatial coverage of the 11 sites with visibility observations of sufficient quality for trend analyses might appear to be incomplete. For example, this study does not include an observational site in large parts of the Swiss plateau and only one site south of the Alps was available. However, this is not considered to be a main limitation for the conclusions drawn. In particular atmospheric PM concentrations are rather homogenious on regional scale and the findings from high quality observations at sites such as Basel-Binningen and Genéve-Cointrin can be considered as representative for large parts of Switzerland.

The physics of visibility is well-known and reveals the relationship between air quality and visibility. Therefore, no formal investigation of this linkage was attempted. In contrast, this study is focusing on descriptive data analyses for the evaluation and explanation of the temporal changes of horizontal visibility across Switzerland.

Mean visibility was found to be increasing significantly across most of Switzerland during the analysis period at a maximum rate of 440 $m\,y^{-1}$. Additionally, days experiencing low visibility conditions including fog ($\leq$ 5000 m) significantly decreased over time, while conversely, extremely clear conditions ($\geq$ 30 km) significantly increased for most locations analysed. Consistent and general weekday patterns of horizontal visibility were identified across Switzerland. The higher visibility on weekends and on Mondays compared to Thursdays and Fridays illustrates the important role of anthropogenic (secondary) PM on atmospheric visibility.

RH is an important driver of visibility due to how it effects particle size and scattering attributes. RH and visibility were explored together and visibility was found to be strongly negatively correlated with RH. For most of the investigated sites, visibility improved in all RH conditions between 1980 and 2018. This was most clearly seen at Basel-Binningen and Genève-

Cointrin. The improving visibility under different RH conditions can clearly be attributed to the improving air quality and particularly to the decreasing PM concentrations across Switzerland.

A clear distinction was found between the high altitude, mountainous sites and those locations at lower altitudes. At higher altitudes air pollutant concentrations and absolute temporal changes in air pollutant concentrations are lower than in regions at lower altitudes due to the proximity to emission sources and the vertical stability of the air at ground-level. Consequently, changes in the horizontal visibility are at high altitude sites smaller than at low altitude sites.

4.1 Outlook

The most obvious continuation or extension of the analysis presented here is to formalise the relationship between visibility and air quality. A likely fruitful approach would involve the use of statistical or machine learning models. Multiple linear regression (MLR), generalised additive models (GAMs),[26] or the random forest algorithm[27,28] could be appropriate techniques. Models of these types could be used to explain visibility by a number of meteorological and time variables. With a quick probe of explanatory power using random forest for the sites with PM_{10} data, the models had R^2 values around 75 % and the variables which were found to be most important for prediction were RH and PM_{10} (Figure 16). This confirms what is known about the primary processes which drive atmospheric visibility.

The formulation of the random forest model can be expressed by Equation 4:

$$V = f\,(T + W_d + W_s + RH + PM_{10} + t_t + t_s + d) \tag{4}$$

Where T is air temperature, W_d and W_s are wind direction and speed respectively, RH is relative humidity, PM_{10} is PM_{10} concentration, t_t and t_s are the trend and seasonal terms, and d is weekday. Other models would likely take a similar form.

A major limitation of the analysis presented and future research is the nature of the visibility observations. As discussed, the monitoring of visibility is not done in Switzerland with the intention of long-term trend analysis and therefore, there are challenges in using the observational record in this way. This will need to be considered and addressed robustly for future work with better data homogenisation and/or filtering, or perhaps only focusing on the handful of sites with the highest quality time series.

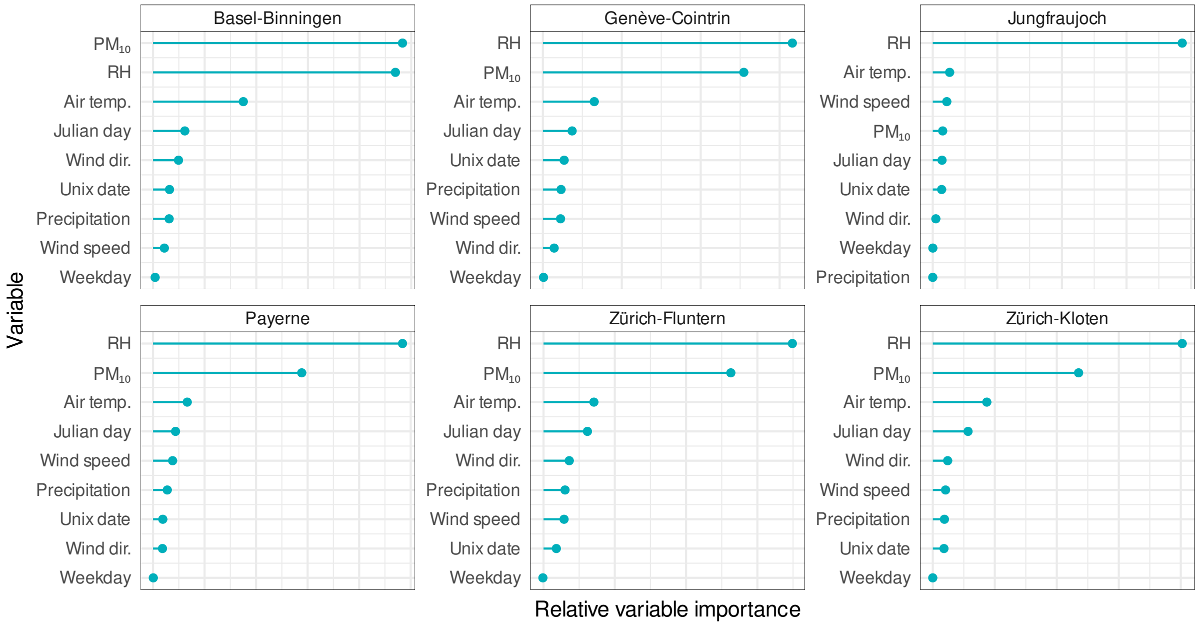

Figure 16: Variable importance plot for five sites' random forest models predicting visibility. Relative humidity (RH) and PM_{10} are consistently found to be important for visibility prediction.

Acknowledgements

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Data availability

The joined data set containing all observations from different sources is available on request. However, please note, permission will need to be sorted from MeteoSwiss before this set can be shared with other parties.

5 Supplementary information

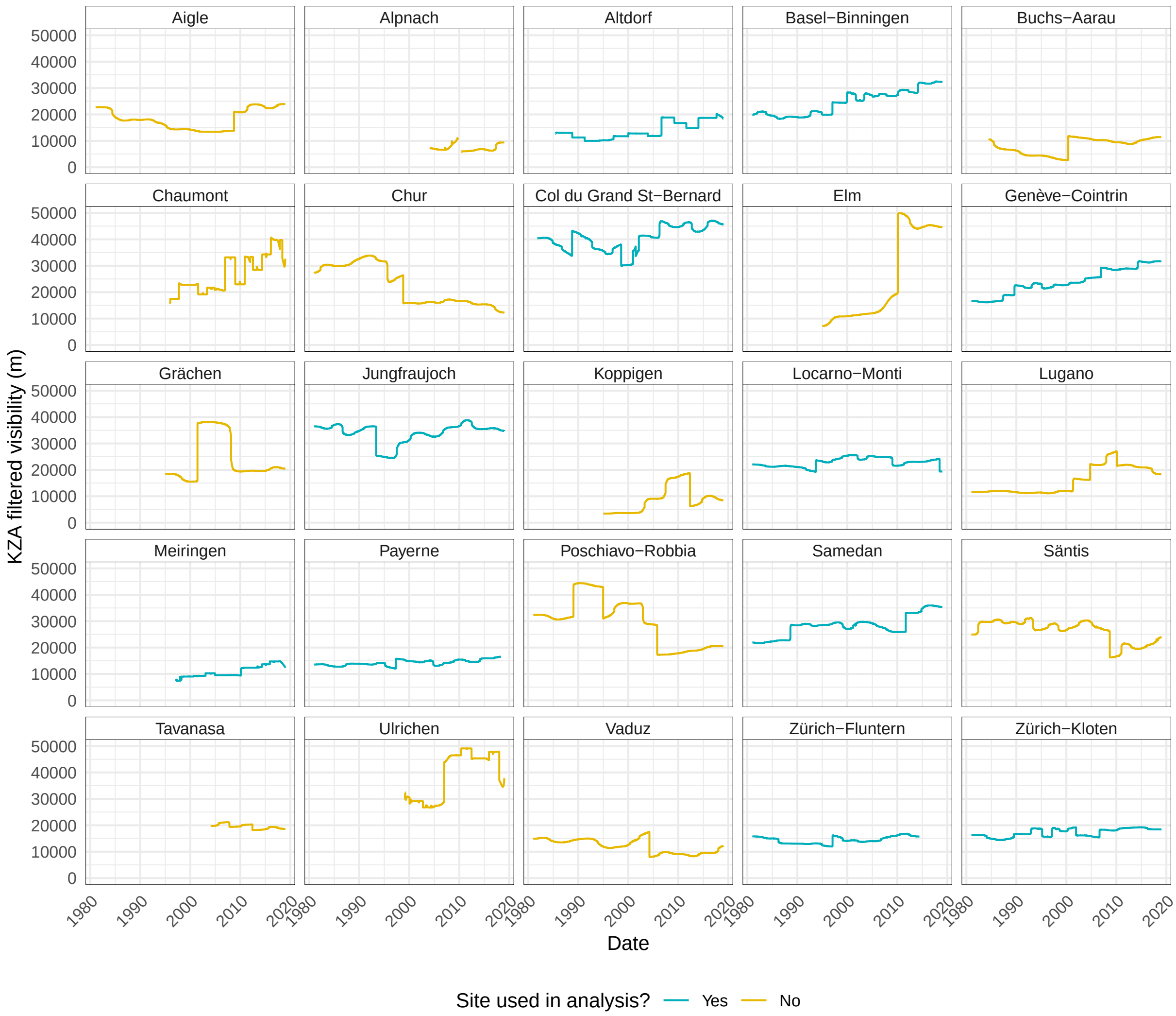

Figure SI 1: Adaptive Kolmogorov-Zurbenko (KZA) filtered visibility time series for all 25 sites which were supplied in the data delivery. The KZA parameters were 365 and 3 for the window-size and number of iterations respectively.

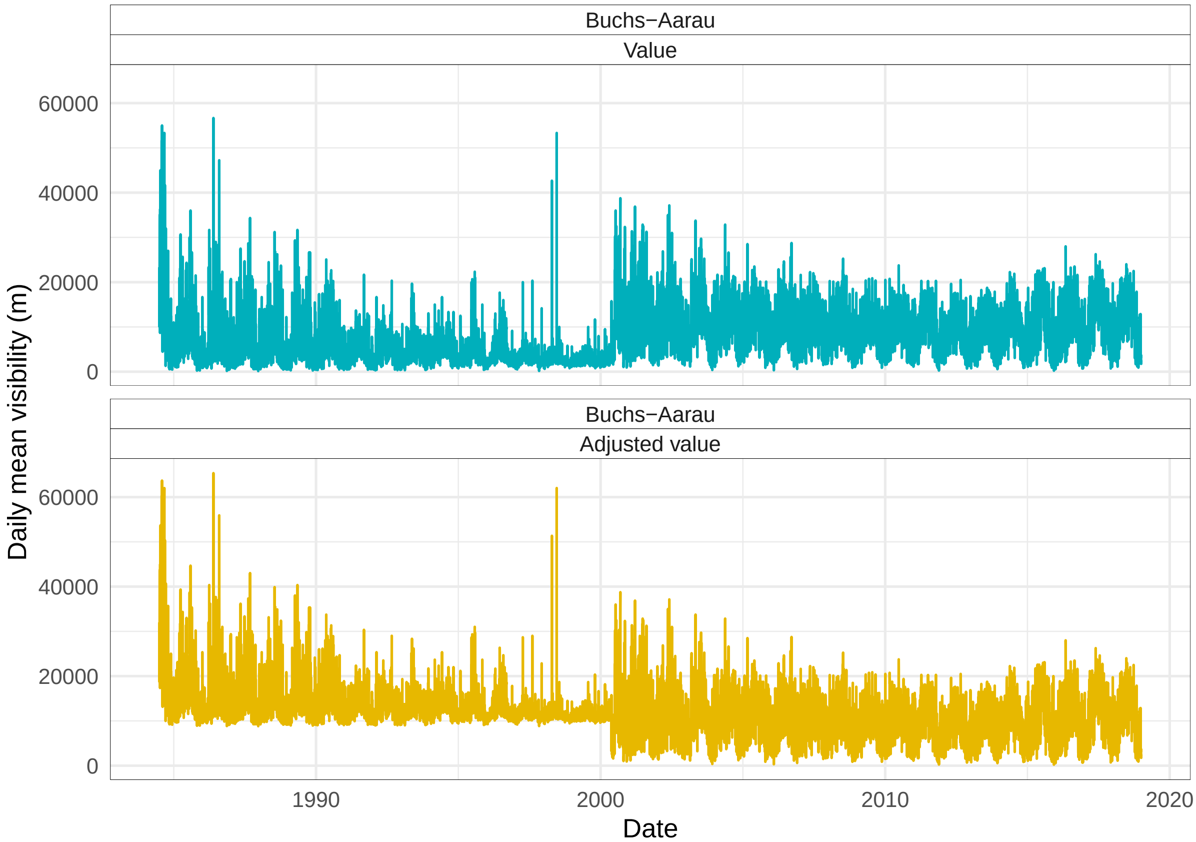

Figure SI 2: An example of applying an offset to a time series for Buchs-Aarau. The discontinuity in the time series is not simply an offset — it is a distribution change which is difficult to homogenise.

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