Causes for decadal trends in Surface Solar Radiation in the Alpine region

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Abstract

Extending across seven countries, the Alps represent an important element for climate and atmospheric circulation in Central Europe. Its complex topography affects processes on different scales within the atmospheric system. This is of major relevance for the decadal trends in Surface Solar Radiation (SSR), also known as Global Dimming and Brightening (GDB). In this study we analysed data from 14 stations in and around the Swiss and Austrian Alps, over a period ranging from the 1960s up to the 2010s, with the aim of characterizing the spatio-temporal variations of the GDB and understanding the causes for such trends in this region. Our results showed a different behavior in the SSR decadal trends in the western part of the Alps in comparison to the eastern part. We also identified a remarkable difference between the causes of such trends in the stations at low altitudes in comparison to the station at higher altitudes. The SSR trends under cloudy conditions revealed strong evidence for a control of the decadal trends by cloud optical depth at high elevation sites, in contrast with a strong clear-sky forcing at low elevations. Results from previous literature and available data suggest that such phenomena could be associated with the indirect and direct aerosol effect, respectively, due to differing pollution levels.

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Key Points:

- Causes for decadal trends in surface solar radiation were identified at 14 stations at different altitudes in the Swiss and Austrian Alps.
- Stations from western and eastern Alps show different phases and transition periods in decadal trends of surface solar radiation.
- Strong evidence indicates that changes in cloud optical depth are the main responsible for these decadal trends at high elevation stations.

Abstract

Extending across seven countries, the Alps represent an important element for climate and atmospheric circulation in Central Europe. Its complex topography affects processes on different scales within the atmospheric system. This is of major relevance for the decadal trends in Surface Solar Radiation (SSR), also known as Global Dimming and Brightening (GDB). In this study we analysed data from 14 stations in and around the Swiss and Austrian Alps, over a period ranging from the 1960s up to the 2010s, with the aim of characterizing the spatio-temporal variations of the GDB and understanding the causes for such trends in this region. Our results showed a different behavior in the SSR decadal trends in the western part of the Alps in comparison to the eastern part. We also identified a remarkable difference between the causes of such trends in the stations at low altitudes in comparison to the station at higher altitudes. The SSR trends under cloudy conditions revealed strong evidence for a control of the decadal trends by cloud optical depth at high elevation sites, in contrast with a strong clear-sky forcing at low elevations. Results from previous literature and available data suggest that such phenomena could be associated with the indirect and direct aerosol effect, respectively, due to differing pollution levels.

Plain Language Summary

The incidence of surface solar radiation (SSR) is not constant nor spatially homogeneous over decades around the globe. It undergoes trends, also known as Global Dimming (negative) or Brightening (positive). Such trends can have different causes, such as changes in cloudiness and aerosol concentrations. In regions with complex topography, like the Alps, understanding the processes leading to such trends might be challenging. In this study we investigated the causes of decadal trends in SSR at 14 stations in the Alpine region. The results show distinctly different decadal trends in SSR between the stations in the western and those in the eastern part of the Alps. We also identified that altitude plays a major role for the causes of the trends. While at low elevations changes in aerosol concentrations seem to largely control long-term SSR, at high altitude stations the changes in optical properties of clouds seem to dominate. This effect might be, however, also associated with changes in aerosol concentrations, since the amount of aerosols present in the cloud formation process has significant effects on the cloud optical properties.

1 Introduction

The complexity of the Alpine region topography represents a challenge for many atmospheric and climate studies. In complex terrain, orographic forcing and local circulation features generate several phenomena which cover different scales of the atmospheric processes (Serafin et al., 2018). From the radiative perspective, this is especially important because it affects key components of the energy balance, such as the aerosol transport (Rotach and Zardi, 2007) and cloud formation. Previous studies have investigated the energy budget in the alpine region (e.g. Ruckstuhl et al., 2007; Philopona, 2013), but the causes of decadal trends in Surface Solar Radiation (SSR) have not yet been deeply explored with focus on the Alpine region and its complex terrain.

Also known as Global Dimming and Brightening (Gilgen et al., 1998; Wild, 2005; Wild 2009), decadal trends in SSR have been an object of study for decades, due to their importance for various aspects of the climate system such as the hydrological cycle and energy budget. Pioneering studies in the late 80s and early 90s (e.g. Ohmura and Lang, 1989; Russak, 1990;

Dutton et al., 1991; Stanhill and Moreshet, 1992) have for the first time presented evidence that the SSR was not constant over time, but exhibited decadal trends. Later publications (e.g. Wild 2009) have pointed out three main periods in the 20th century over Europe: a positive trend before the 50s also referred to as "early brightening"; a negative trend between the 50s and the 80s also referred to as "dimming"; and a follow-up period of positive trends also known as "brightening".

Regarding the causes of GDB, several studies (e.g. Power, 2003; Wild et al, 2005; Streets et al., 2009; Manara et al., 2016, Wild et al., 2021) have attributed the dimming and subsequent brightening in Europe to changes in aerosol loadings. Changes in emission regulations enforced from the 80s onwards in many European countries might have been a major cause for the decrease in AOD, which reduced the direct aerosol effect in most of Central and Southern Europe and resulted in an increase of SSR (brightening period). Other authors (Stjern et al., 2008) associated the GDB trends in northern Europe with changes in cloud cover. Even though Krüger and Graßl (2002) have identified a pronounced decrease in cloud albedo in Europe during the period of decreasing aerosols in the 80s and 90s, Ruckstuhl et al. (2010) did not find evidence of a significant indirect aerosol effect on SSR changes at 15 lowland stations (altitude lower than 1000 masl) in Switzerland during the same period. Folini et al. (2017) and Chtirkova et al. (2022) highlighted that the effect of internal variability at individual locations should not be neglected. All of these studies provide evidence for the existence of different players controlling the decadal SSR trends, from both natural and anthropogenic origins. Thus, a careful analysis is required to link SSR decadal trends to their causes.

In the present study, we analyze the spatio-temporal variations of the decadal trends in SSR in the alpine region and its underlying causes, contrasting the trends and causes in different parts of the Alps and at different altitudes. For this purpose we use data from 14 stations in and around the Swiss and Austrian Alps, at different altitudes. The time span depends on the data availability at each station, but ranges from the 1960s to the 2010s. The objective is to answer whether the GDB trends in the region are similar within the whole mountain range and to understand which processes control the trends in different areas and at different altitudes.

2 Data and Methods

SSR daily means from 14 stations in the Swiss and Austrian alpine region ranging from the 1960s until the 2010s were used in this study. They are listed in Table 1 and shown in Figure 1. This data was collected from the World Radiation Data Center (WRDC - Voeikov Main Geophysical Observatory, 2022), from the European Climate Assessment and Dataset (ECAD - Klein Tank et al., 2002) and from the website of the Federal Office of Meteorology and Climatology of Switzerland (IDAWEB, Meteoswiss), which all provide data with at least daily resolution. Daily resolution is a prerequisite for the estimation of clear-sky trends as described in Correa et al. (2022). Their altitudes range from 203 to 3580 meters above sea level. Synop cloud cover (oktas) and sunshine duration were collected, when available, from ECAD. For Jungfraujoch, Synop cloud cover data was obtained via the ogimet website (https://www.ogimet.com/synops.phtml.en). Particle Number Concentration and Cloud Condensation Number Concentration at Jungfraujoch were downloaded from EBAS (Tørseth et al., 2012), a database operated by the Norwegian Institute for Air Research (NILU). ERA-5 reanalysis data (Hersbach et al., 2020) was also used.

Station	Coordinates	Altitude (m)	Topography	Synop cloud cover/Sunshine duration available?	Availability	Source
Col du Grand St-Bernard, Switzerland (GSB)	45.87°N 7.17°E	2472	High altitude valley	Yes/Yes	1981-2019	IDAWEB
Feuerkogel, Austria (FKG)	47.82°N 13.73°E	1598	Mountain peak	Yes/Yes	1965-1988	ECAD
Geneva, Switzerland (GNV)	46.25°N 6.13°E	420	Low elevation urban	Yes/Yes	1981-2018	WRDC
Guestsch, Andermatt (GUE)	46.65°N 8.62°E	2286	Mountain peak	No/No	1981-2019	IDAWEB
Innsbruck, Austria (INN)	47.25°N 11.35°E	579	Mountain valley urban	Yes/Yes	1968-2018	WRDC
Jungfraujoch, Switzerland (JFJ)	46.55°N 7.98°E	3580	Mountain peak	Yes/No	1981-2018	WRDC
Pitztaler Gletscher, Austria (PTG)	46.92°N 10.87°E	2864	Mountain peak	No/No	1994-2021	ECAD
Piz Corvatsch, Switzerland (COR)	46.42°N 9.82°E	3315	Mountain peak	No/No	1981-2018	WRDC
Saentis, Switzerland (SAE)	47.25°N 9.35°E	2490	Mountain peak	Yes/Yes	1981-2018	WRDC
Salzburg, Austria (SZB)	47.78°N 13.05°E	420	Low elevation urban	Yes/Yes	1964-2018	WRDC
Sonnblick, Austria (SON)	47.05°N 12.95°E	3105	Mountain peak	Yes/Yes	1964-2018	WRDC
Weissfluhjoch, Switzerland (WFJ)	46.83°N 9.80°E	2691	Mountain peak	No/No	1981-2019	IDAWEB
Vienna, Austria (VIE)	48.25°N 16.35°E	203	Low elevation urban	Yes/Yes	1964-2018	WRDC

Zurich, Switzerland (ZRH)	47.48°N 8.53°E	436	Low elevation urban	Yes/Yes	1981-2018	WRDC

Table 1 - Map of the altitudes (in meters) of the Alpine region and the location of the stations used in this study.

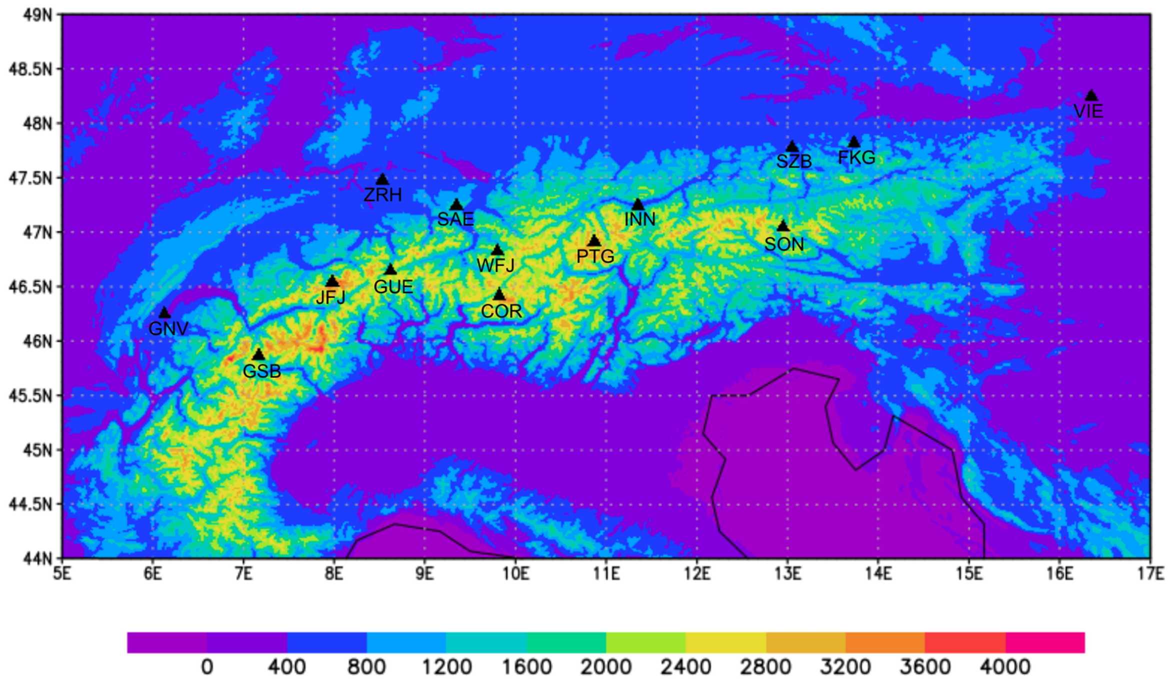

Figure 1 - Map of the altitudes (in meters) of the Alpine region and the location of the stations used in this study.

Clear-sky SSR time series were derived from the daily data based on 2 different methods: using (1) the method by Correa et al. (2022) and using (2) Synop cloud cover data (when available). In (1), satellite cloud cover daily data is used as a proxy for clear-sky occurrence at each station. Then, by combining satellite cloud cover and transmittance data at the station (directly associating the station to its closest grid from the satellite data), optimal monthly transmittances thresholds are retrieved to remove days in which clouds significantly affected the transmittance, resulting in clear-sky time series. As the resulting time series contains missing data on all days flagged as cloudy, special attention is required when converting daily data into monthly and annual values. Monthly values are only calculated when at least 2 days flagged as clear-sky occur, otherwise the climatology is used. When calculating monthly means, the irradiance at the days flagged as clear-sky is normalised to the 15th day of the month, to avoid bias due to solar geometry. Annual values are the mean of the 12 normalised monthly means, but are calculated only when at least 10 out of the 12 months had enough available data (i.e. no more than 2 months have the monthly value expressed as the climatology). This normalisation process when going from daily to monthly and then annual data is repeated in all further derivations used in this study (Synop clear-sky, overcast and true overcast time series). In the method (2), based on Synop cloud cover, we considered any days with 2 or less oktas of cloud cover as clear-sky, with the conversion from daily to monthly and annual values as described above.

Clear-sky time series allow the assessment of the cloud-free processes in the atmosphere, such as the SSR changes due to direct aerosol effect or the changes in water vapor content. In combination with all-sky SSR time series and cloud cover time series, it provides insight to the most important aspects regarding the SSR decadal variability. However, the context of this study also requires an assessment of the SSR variability due to cloud optical depth. The obvious choice to achieve this is to derive a SSR overcast time series using Synop cloud cover information, flagging all days with 8 oktas of cloud cover as overcast, as done in previous studies (e.g. Ruckstuhl et al., 2010). Nevertheless, these time series would still retain the SSR variability due to changes in cloud type. Ruckstuhl et al. (2010) have reported a positive trend in high clouds and a negative trend in cumulus clouds over Switzerland under overcast conditions in the period from 1981 to 2005. This "change" from low to high clouds would obviously exert a positive forcing on SSR, since high clouds are more transmissive to solar radiation. In order to minimize this effect in the SSR time series while keeping the effects of changes in cloud optical depth, we adapted the method by combining the Synop cloud fraction observations with sunshine duration observations. We used only days with 8 oktas of Synop cloud fraction and 0.0 hours of Sunshine duration to derive time series that from here on will be called "true overcast" SSR. Alternatively, this could have been done with information from low/high level clouds from Synop observations, which, however, was not available for this study. With these time series, we expect to avoid any days with non-overcast periods and days when the overcast condition is mostly due to high clouds, since, on such days, one would expect the heliograph to report non zero sunshine duration values. Comparisons between overcast and true overcast time series have shown irradiances up to 20% smaller in the latter, in addition to differences in the long term trends. All the trends presented in this study are calculated from the 11-year moving mean time series.

3 Results

We first present observational time series of all-sky and clear-sky SSR for the different sites in Sections 3.1 and 3.2. Next, we examine in Section 3.3.1 cloud cover data and discuss its potential to explain the SSR observations presented, highlighting that cloud cover changes on their own cannot explain all aspects of observed all-sky SSR changes at most sites. Consequently, we turn to cloud optical depth in Sections 3.3.2 to 3.3.4, using SSR under true overcast conditions as a proxy. Finally, in Section 3.3.5 we discuss the contrast of what was observed at Piz Corvatsch compared to the other stations, and potential reasoning for the deviations at this site in the southern Alps.

3.1 Spatio-temporal homogeneity of SSR decadal variability in the alpine region

Figure 2 shows the time series of SSR annual anomalies in 12 out of the 14 stations analyzed in this study. As can be seen in table 1, the stations not shown have the shortest time spans. Most stations show a negative trend in SSR until the 1980s or 1990s, which turn into positive trends after that, agreeing with what was published in previous studies (e.g. Wild et al., 2005). A few aspects, however, should be highlighted. First, all of the Austrian stations analyzed show, at the turn of the century, a slow down or even change in the positive SSR trends observed in the previous decades. The trends after 1995 at these stations range from 1.8 W/m^2 per decade in Salzburg (not statistically significant at the 0.05 level) to -2.20 W/m^2 per decade at Sonnblick (statistically significant at the 0.05 level). In the same period, the Swiss stations show an intensification in the positive all-sky SSR trends. Figure 3 shows this contrast between the trends in the western and in the eastern part of the Alps before and after 1995. Secondly, even though almost all of the Swiss stations show statistically significant positive trends in the period after 1995, the change from negative/stable to positive trends is not homogeneous timewise. In Geneva, for example, the strong increase in SSR started only around 2000, when most Swiss stations already were showing strong positive trends. Finally, at the high altitude site Piz Corvatsch, in southeastern Switzerland, one cannot identify any clear change in trends. The site shows strong interannual variability, but the long term trends are mostly stable, at 0.031 W/m^2 per decade in the period from 1981 to 2018. All of this reveals a non-homogeneous spatio-temporal SSR decadal variability in the alpine region, which suggests that more than one process could be of significance for the decadal SSR variability in the region.

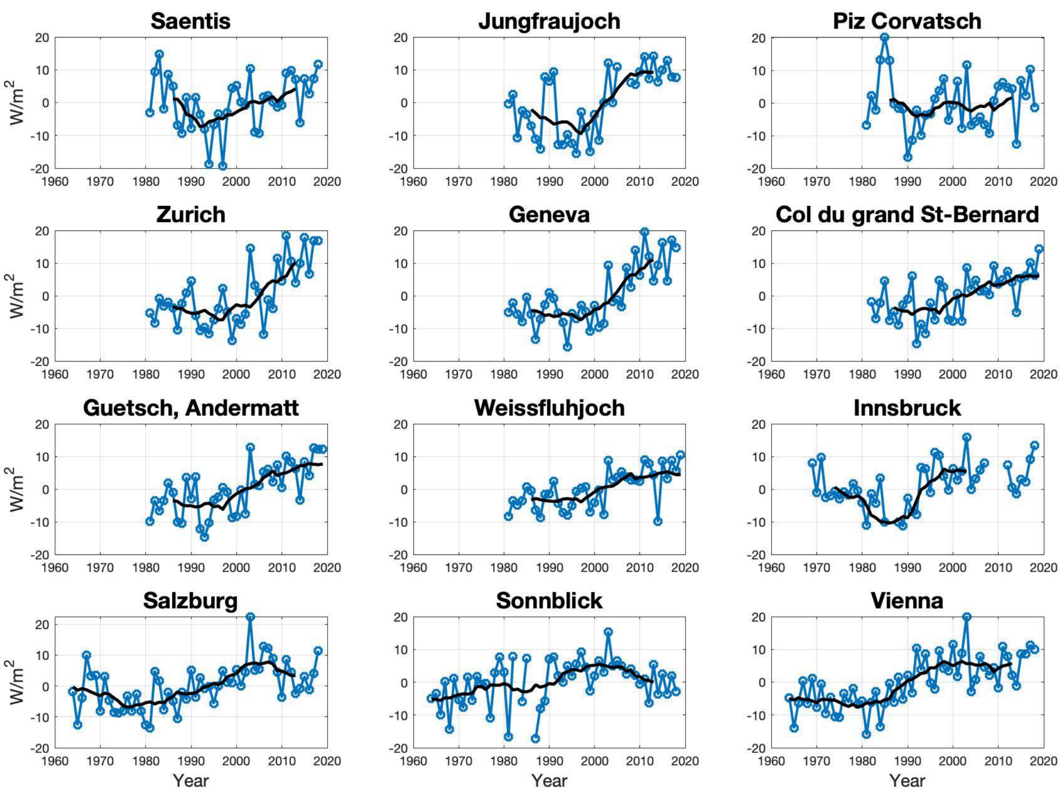

Figure 2 - All-sky SSR anomalies time series at 12 of the 14 stations analyzed in this study. Black line represents the 11-year moving means. Of the stations not included, Feuerkogel has data only before 1989 and Pitztaler Gletscher has data only from 1994, with a gap between 2000 and 2007.

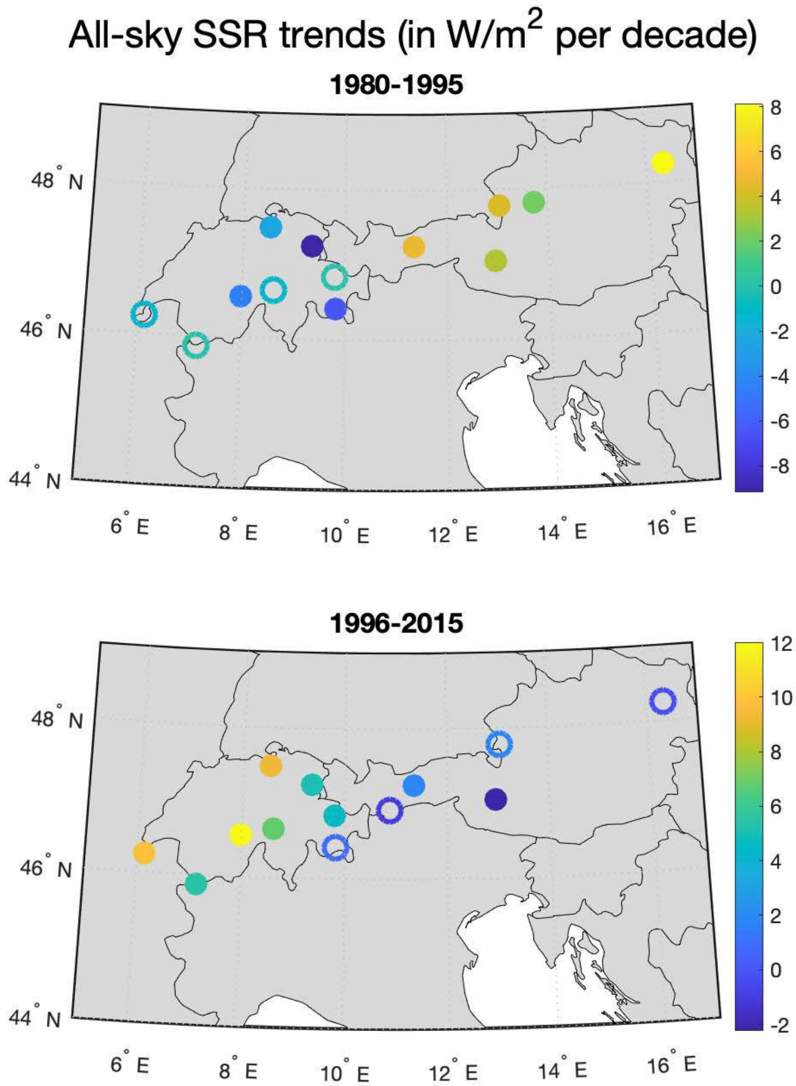

Figure 3 - Map of all-sky SSR trends at the stations used in this study for two periods (1980-1995 and 1996-2015). Filled markers indicate statistically significant trends at 0.05 level. Both maps include 13 stations because Feuerkogel covers only the first period and Pitztaler Gletscher only the second.

3.2 Aerosols as a cause for SSR decadal trends: clear-sky SSR

Figure 4 shows the time series of clear-sky SSR annual anomalies at 12 stations, based on the two different methods outlined in section 2. These time series are expected to show the variability when clouds do not play a role. Under these conditions, most stations keep the general behavior of the all-sky SSR: The Austrian stations with stable to negative trends in the 21st century and the Swiss stations with positive trends in the same period. However, this is not the case for Jungfraujoch and Saentis. At both sites a persistent stable to negative trend is observed in clear-sky while in all-sky positive trends take place. This disagreement between all-sky and clear-sky SSR trends is a strong indication that clouds might be responsible for the observed trends in all-sky.

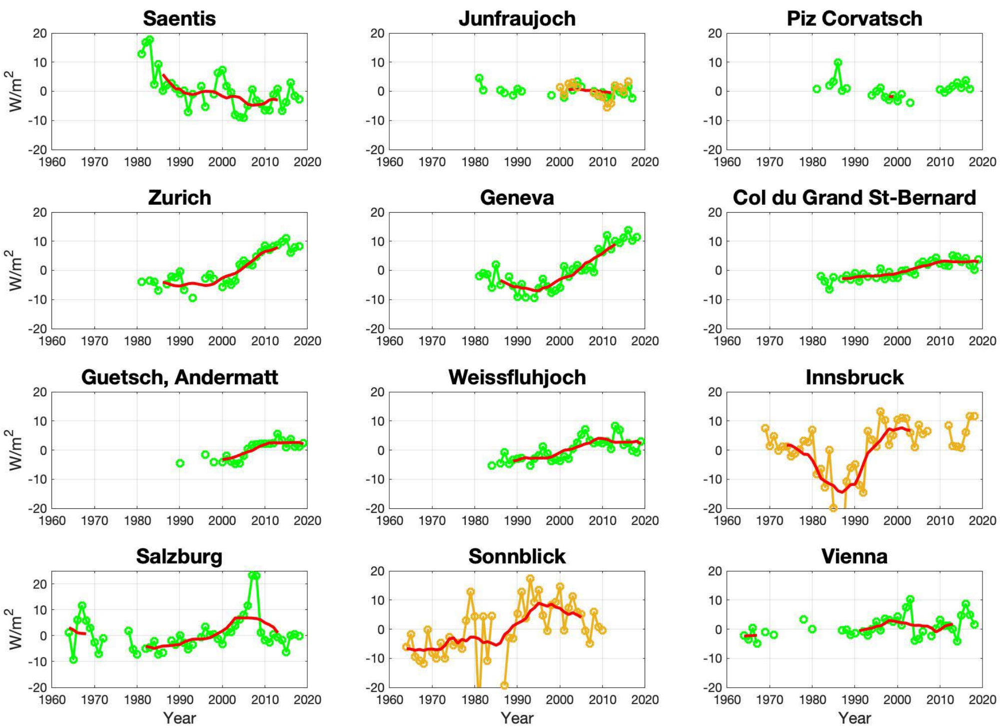

Figure 4 - Clear-sky SSR anomalies time series at 12 of the 14 stations used in this study. Time series in green were derived with the method by Correa et al., (2022) and time series in orange were derived with SYNOP cloud cover data. Jungfraujoch with both time series for comparison due to too many missing years in the first method; Innsbruck and Sonnblick only have SYNOP derived clear-sky due to too many missing years in the other method; other stations with both clear-sky time series presented similar long-term behavior, but have only one plot presented for simplification. The red line represents the 11-year moving means.

The analysis of the individual time series also reveals a contrast between low elevation and high elevation stations. At lower altitudes, such as at the stations Zurich or Salzburg, the magnitudes of the clear-sky trends are much higher than at higher altitude stations. At the Zurich station, for example, the clear-sky trend after 1995 is 8.1 W/m^2 per decade, which is equivalent to 86% of the all-sky trend. The same comparison for Col du Grand St Bernard reveals that the clear-sky trend is equivalent to only 50% of the all-sky trend. This pattern is repeated at most sites, with the exception of Sonnblick and Vienna. At Sonnblick, a high elevation site, both the clear-sky trends before and after 1995 show the same sign but with higher magnitude compared to those in all-sky (clear sky represents 195% of all-sky before 1995 and 218% after 1995), and in Vienna, a low elevation site, a much smaller trend is found under clear-sky than all-sky conditions. The overall pattern indicates that, at lower elevations, cloud free processes play a major role in controlling SSR decadal trends. This is in line with previous studies which associated the changes in SSR decadal trends in Europe mostly to changes in aerosol loadings, which prevail in low level boundary layers (e.g. Wild et al, 2005; Streets et al.,2009; Manara et al., 2016, Wild et al., 2021) (see also discussion section).

3.3 The role of clouds and aerosols in the decadal SSR trends

The comparison between all-sky and clear-sky SSR changes revealed the most significant differences at stations at higher altitudes and the most significant similarities at lower altitudes. Regarding the differences, the stations Saentis and Jungfraujoch are especially remarkable, since, their clear-sky long term variability do not show a recovery from the dimming period. This implies that clouds should be the main responsible for the all-sky SSR trends at these high altitude sites. At low elevations, the similarities between all-sky and clear-sky time series imply that the cloud-free processes dominate over the cloud effects. This does not apply, however, to Vienna. At this low elevation Austrian station the clear-sky time series shows little variability in the long term, contrasting to a significant positive trend in all-sky between the 1980s and the turn of the century.

3.3.1 Changes in cloud cover in the western and eastern Alps

The logical sequence to initially verify the role of clouds at each station is through an analysis of the changes in cloud cover, which we pursued using information from Synop observations as well as from ERA5 reanalysis. In figure 5 we display the cloud cover time series for the two mentioned high elevation sites, for Vienna and for three low land sites (two in Switzerland and one in Austria). For Jungfraujoch the ERA5 cloud cover is plotted together with SYNOP cloud cover due to the limited period of the second, but for the other stations only SYNOP cloud cover is plotted for simplification. At the sites Saentis, Salzburg, Jungfraujoch and Zurich, no significant cloud cover changes in line with the positive trends in all-sky SSR was observed. At Geneva, a period of approximately 10 years of decreasing cloud cover from the mid 1990s to the mid 2000s (-2.8% per decade, statistically significant) might have contributed to the positive trend in SSR during that period, even though the clear-sky time series (trend after 1995 = 9.0 W/m^2 per decade; ~91% of the all-sky trend) indicates that the clear-sky processes dominate at that station. Finally, in Vienna, a period of more than 20 years of decrease in cloud cover between the late 1970s and the late 1990s (-3.3% per decade, statistically significant) is in line with the observed brightening during this period at the station (7.5 W/m^2 per decade). The comparison between 11-year moving mean SSR and cloud cover in Vienna show a correlation of -0.96.

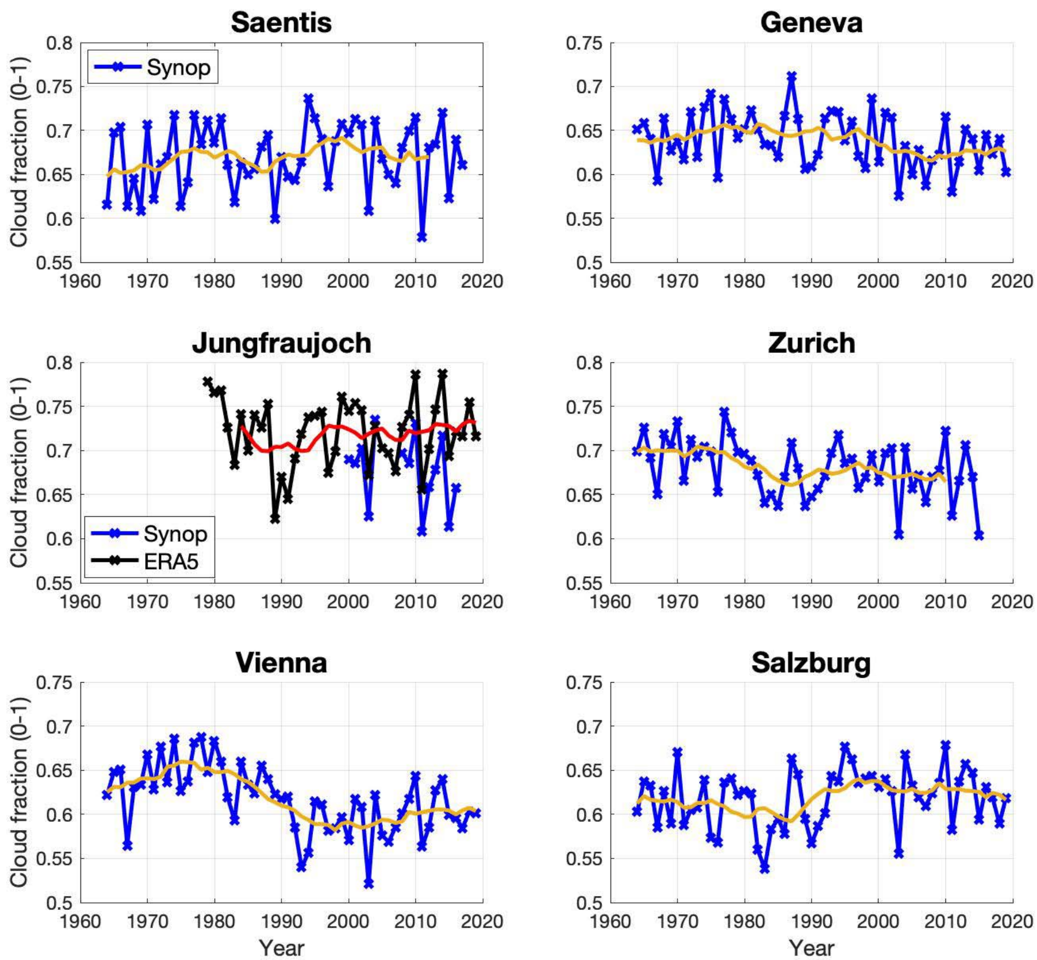

Figure 5 - Cloud cover annual time series at two high elevation and four low land stations in Switzerland and Austria, from SYNOP observations (blue) and from ERA5 reanalysis (black). The orange line shows the 11-year moving means of the SYNOP time series; the red line in the Jungfraujoch panel shows the 11-year moving means of the ERA5 time series.

While in Vienna the observations point towards SSR decadal trends caused by changes in cloud cover, at the other low land stations the clear-sky processes seem to dominate the long term SSR trends. At Saentis and at Jungfraujoch, however, both clear-sky variability and cloud cover trends do not seem to be sufficient to explain the long term SSR trends. The Synop cloud cover at Sonnblick, Feuerkogel and Col du Grand Saint Bernard (not shown) and the ERA5 cloud cover at the grids of the other high elevation stations (not shown) also do not show long term cloud cover trends in line with the all-sky SSR trends.

3.3.2 Aerosols and Cloud Optical Properties

This drives our attention to any potential changes in cloud optical properties at the high elevation stations. Wild (2009) has introduced a conceptual framework on the role of aerosol and clouds in dimming/brightening processes. The author argues that at pristine locations small changes in cloud condensation nuclei potentially have an effective impact on cloud characteristics, thus a small increase in CCNs could result in an amplified reduction in SSR via aerosol indirect effect and vice versa. On the other hand, in highly polluted areas, cloud microphysics effects saturate, and an increase in aerosols may suppress cloud formation, resulting in an opposite effect on SSR trends compared to pristine regions (Wild 2009, 2012). Yang et al. (2021) have demonstrated this effect in China, which can be classified mostly as a highly polluted area. The high elevation Alpine stations analyzed in this study range in altitudes from 1598 to 3105 meters, being located above the lower layers of the atmosphere, where the major sources of aerosols are found and where the aerosol concentrations are usually higher. Thus, in the referred conceptual framework, these stations could be classified as pristine. In this context, one would expect that the period of strong increase in SSR at the Saentis and Jungfraujoch stations would be a period of decrease in CCNs. On Jungfraujoch this could be verified via the Particle Number Concentration (PNC) time series, which is shown in Figure 6.

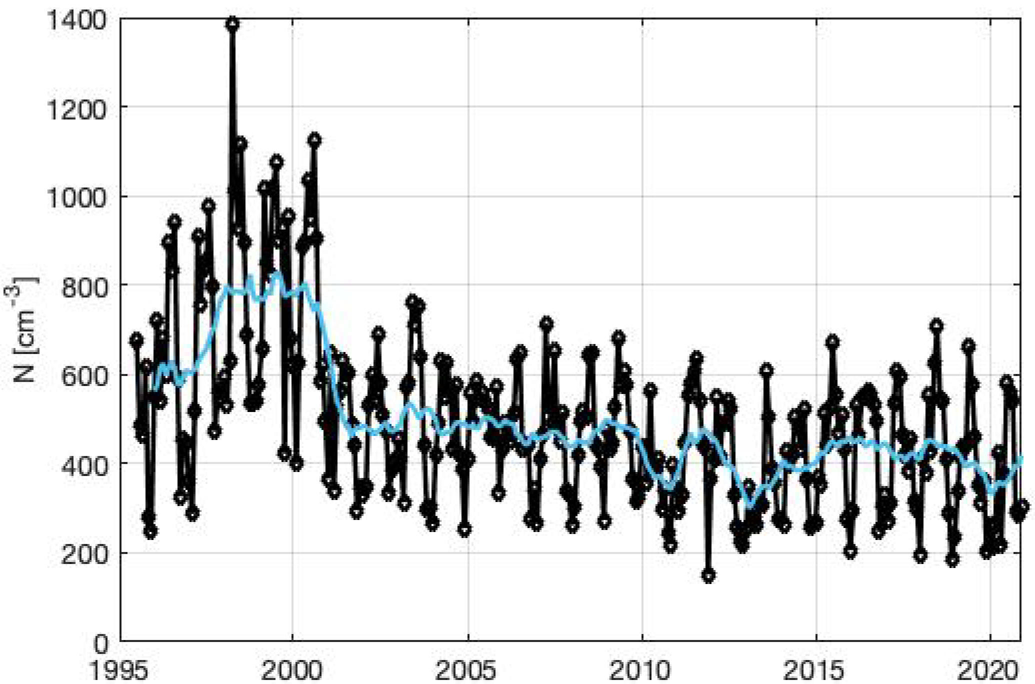

Figure 6 - Particle Number Concentration monthly time series at Jungfraujoch. Blue line shows the 12 month moving mean.

At the Jungfraujoch station there is a decrease in particle number concentration at the turn of the century, which fits to the period of stronger positive trend in SSR at that station. The time series of monthly anomalies of all-sky SSR has a correlation of -0.735 with the monthly PNC. Cloud condensation nuclei number concentration (CCNNC) data was available only from 2012, but comparisons between PNC and CCNNC time series in the overlapping period between the two measurements show strong correlations, ranging from 0.65 at 0.1% super saturation to 0.78 at 1% super saturation in the monthly means time series. According to the referred conceptual framework, this decrease in PNC would result in less bright clouds with shorter lifetimes, allowing for more solar radiation to reach the surface.

3.3.3 True overcast SSR changes as a proxy for Cloud Optical Depth changes

Aerosol measurements require a highly specialized instrumentation, and, for that reason, not all stations have such measurements. Thus, in order to assess the effects of changes in cloud optical depth on SSR we used the time series of true overcast SSR (introduced in section 2) as a proxy. Figure 7 shows the true overcast time series for the stations where both synop cloud cover and sunshine duration data was available. We did not have the sunshine duration data from Jungfraujoch, but we believe that this is an important site for the discussion, thus at this site the time series shown is the overcast SSR (not "true overcast", thus based on Synop data only).

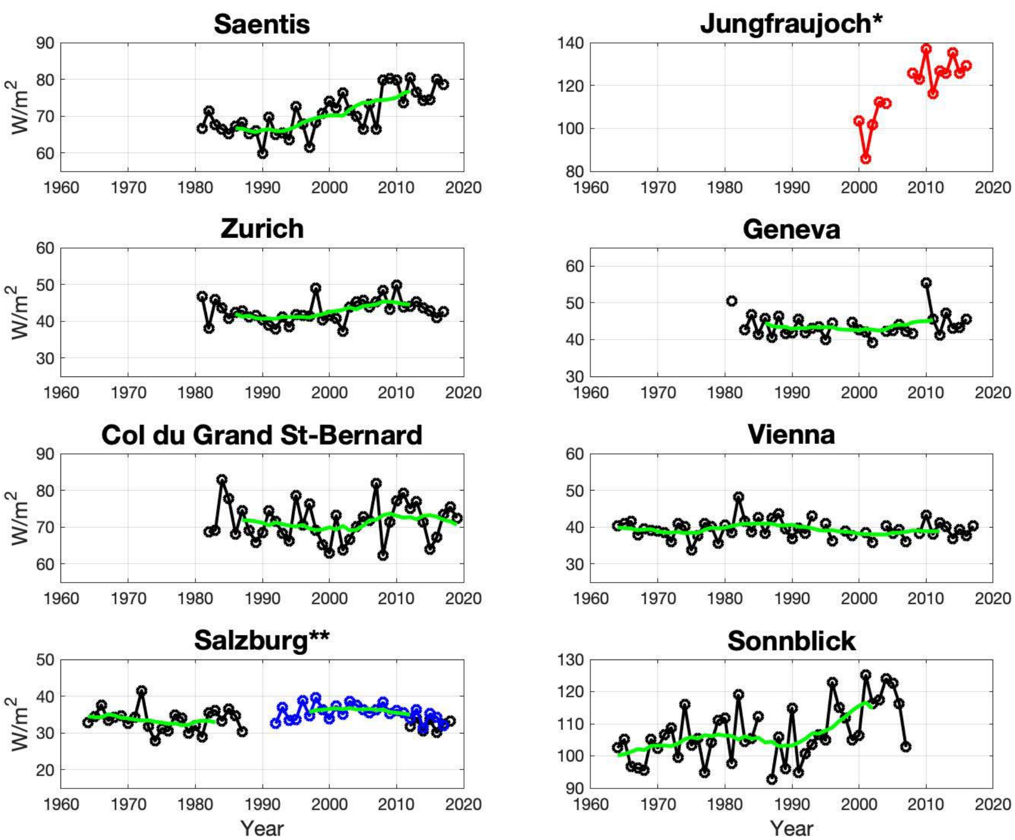

Figure 7 - True overcast SSR annual time series of stations used in this study. Green lines show the 11-year moving means.
*Sunshine duration data at Jungfraujoch was not available, thus, its red line shows the overcast time series (only days with 8 oktas of cloud cover) instead of the true overcast time series (only days with 8 oktas of cloud cover + 0.0 hours of sunshine duration).
**The Salzburg time series is using a combination of the sunshine duration and cloud cover from Salzburg airport (black part) and Salzburg Freisaal (blue part) for the true overcast determination. The irradiance data was collected at Salzburg Freisaal. Stations are ~5km apart.

One can note from the time series in Figure 7 that interannual variability is higher at high elevation stations. This is also reflected in the decadal trends. On Saentis, the decadal trend after 1992 (brightening phase) is 5.5 W/m^2 per decade, while in Zurich it is 2.5 W/m^2 per decade. When compared to the all-sky trends, 5.2 and 8.2 W/m^2 per decade respectively, the true overcast trends are equivalent to 105.7% of the all-sky trends at Saentis and 30.9% at Zurich. The overcast time series at Jungfraujoch also shows a remarkable positive phase which fits with to the positive phase in the all-sky time series. Nevertheless, since the overcast time series at Jungfraujoch is only based on synop cloud cover, it can be affected by non overcast periods in between the synop measurements and by overcast conditions by high clouds. Anyhow, the pattern of higher variability and stronger trends at high elevations is consistent with other stations. An exception here is Col du Grand Saint Bernard. Its true overcast trend after 1992 of 1.25 W/m^2 per decade is smaller even than the low elevation sites. The reason for this contrast could be in the local features. Differently to the other high elevation sites, Col du Grand Saint Bernard is not at the top of a mountain, but rather located in a valley between higher peaks (up to around 400 meters higher). If the hypothesis that changes in cloud optical depth are mostly associated with aerosol indirect effect is correct, the nearby peaks might be shadowing the effect at this station. Such local features, as the contrast between cloud formation processes in a mountain top environment and a valley environment, are relevant for the discussion of the causes of GDB at the local scale, but go beyond the scope of this paper, since here we focus on the larger scale features rather than particularities of every individual station.

3.3.4 The role of the altitude in true overcast SSR variability

In order to visualise the role of altitude in the true overcast time series variability (thus, the importance of the cloud optical depth variability according to altitude), figure 8 shows a comparison of the absolute and relative standard deviations of true overcast annual SSR as a function of altitude.

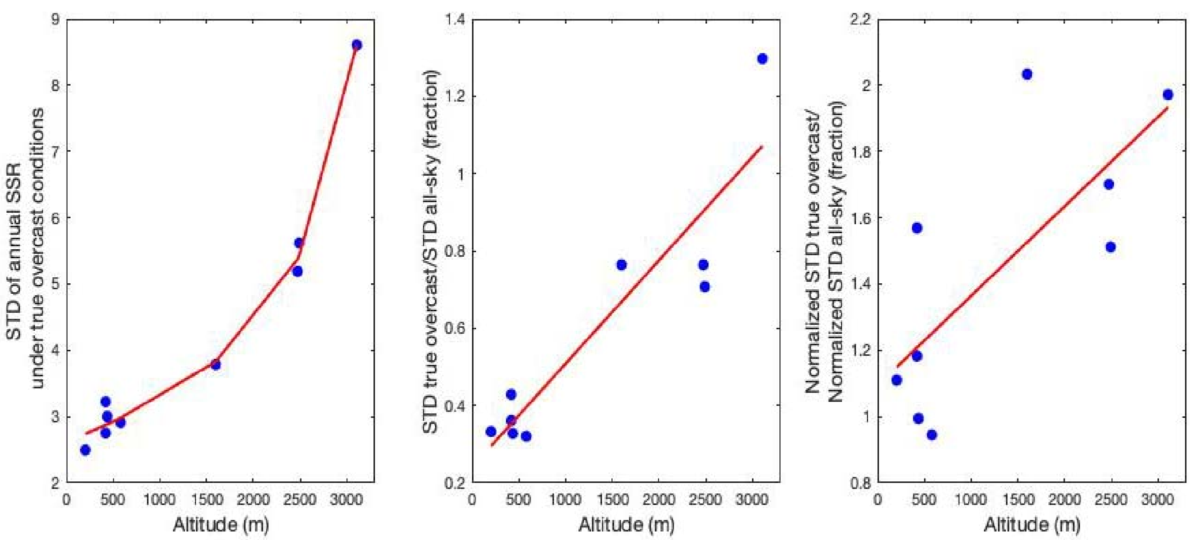

Figure 8 - (a) Comparison between standard deviation of true overcast annual SSR and altitude of the station; (b) Ratio between absolute standard deviation of annual SSR under true overcast and under all-sky conditions vs the

altitude of the station; and (c) Ratio between relative standard deviation (relative standard deviation = standard deviation normalized by the mean SSR) of annual SSR under true overcast and under all-sky conditions vs the altitude of the station.

The simple comparison between standard deviations of annual true overcast SSR and altitude (Figure 8a) reveals an exponential curve. This curve fits to the expected exponential decay of transmittance based on the Beer-Lambert law. Stations at higher altitudes have a smaller depth of atmosphere between them and TOA, thus, since in this comparison all stations have similar cloudiness conditions (i.e., true overcast), they are expected to receive higher irradiance on average. This results in higher variability (in absolute values) at higher altitudes, because any, for example, 10% reduction in transmittance due to changes in cloud optical depth, will be reflected in higher absolute SSR variability in locations with higher mean irradiances. However, when we compare the true overcast variability against the all-sky variability (Figure 8b) we identify a close to linear relationship (R^2 = 0.845). At higher altitudes, the fraction of true overcast divided by all-sky standard deviation is higher than at low altitudes. This might indicate that the SSR variability under true overcast conditions is more relevant to the overall SSR variability at high elevations than at low land stations. In Figure 8c the standard deviations are normalized with the average irradiance under the respective conditions (all-sky or true overcast), so that we see the relative standard deviation (in %) instead of absolute (in W/m^2). In this scenario we still see a statistically significant linear relationship, and the true overcast STD at high altitudes can be as high as twice of the all-sky. In practical terms, this would mean that a station with standard deviation of annual all-sky SSR of 5% could have a standard deviation of 10% under true overcast conditions. This shows that the importance of the true overcast variability (thus, cloud optical depth variability) increases with altitude not only in absolute (W/m^2) but also in relative (%) terms.

It should be highlighted that at the daily times scale, the absolute standard deviation is always higher under all-sky than under true overcast conditions (not shown), as expected. Sonnblick shows the highest daily mean absolute standard deviation under true overcast when compared to all-sky between all the stations, with the value of the first representing 64% of the value of the second. At annual time scales, however, the averaging process masks the stronger day to day variability, and this led, at Sonnblick, to a higher standard deviation under true overcast than under all-sky conditions. This explains the, at first glance unexpected, value above 1 in Figure 8b, which stems from Sonnblick.

These comparisons suggest that the variability under true overcast conditions can in fact represent a significant fraction of the all-sky SSR variability at high elevations. This might be counter intuitive at first, since all-sky variability can happen due to any process in the atmosphere, most remarkably to changes in cloud cover, while the true overcast shows variability mostly due to changes in cloud optical properties. However, the pristine conditions at high elevations can be favorable for the enhancement of the indirect aerosol effect. The higher average irradiance at high elevations under true overcast conditions (Beer-Lambert law) can also enhance this effect, since similar relative changes would result in higher absolute changes at high elevations than at low elevations. It should be noted that other aspects not assessed in this paper (i.e. changes in cloud liquid water content) could also affect cloud optical depth and thus the SSR variability.

Another remarkable aspect of the true overcast SSR annual time series regards the Austrian stations. As previously mentioned, these stations show a reversal in the all-sky trends at the turn of the century. This is, to some extent, also observed in the true overcast time series. Sonnblick, for example, shows a positive trend of 8.0 W/m^2 per decade in the true overcast time series if we take the series from 1990, however, the trend turns negative (-0.5 W/m^2 per decade, not significant) if we take the series starting in 1996. The simple comparison of the annual mean SSR time series under all-sky and true overcast conditions at this site reveals a correlation coefficient of 0.705 (statistically significant) between the two time series in Sonnblick. All of this reveals that, even though the all-sky trends behave different in Austria when compared to the Swiss stations, the all-sky - true overcast similarities can still be identified in the Austrian Alps.

3.3.5 Changes in cloud cover in the Southern Alps: the case of Piz Corvatsch

Finally, Piz Corvatsch shows an interesting SSR decadal variability, not having any distinct positive or negative decadal trend. No sunshine duration or synop cloud cover data was available for this station, which is located in the southern region of the Alps, thus no derivation of true overcast conditions time series was possible. The clear-sky time series at this station, however, shows a change in trend, from a negative trend before the year 2000 to a positive trend after that. This off-phase between all-sky and clear-sky suggests that changes in clouds control the all-sky trends. The significant role of changes in cloud cover in the long term SSR variability at this station gets more evident when the seasons are observed individually. Figure 9 shows the comparison between 11-year moving mean seasonal SSR anomalies and 11-year moving mean seasonal cloud fraction anomalies from ERA5 at Piz Corvatsch. Fall, winter and spring show statistically significant linear correlations of -0.80, -0.74 and -0.64 respectively. In summer, the linear correlation is -0.18 (not significant at the 0.05 level). Other high elevation stations also show statistically significant correlation in some seasons in such comparison. For instance, Saentis also shows a strong negative correlation between 11-year moving means of seasonal anomalies of irradiance and cloud fraction in fall, and Sonnblick in spring (not shown). But neither these stations, nor the other stations analysed in this study show such a remarkable occurrence of multiple seasons with such strong negative correlations between the variables as it was observed at Piz Corvatsch.

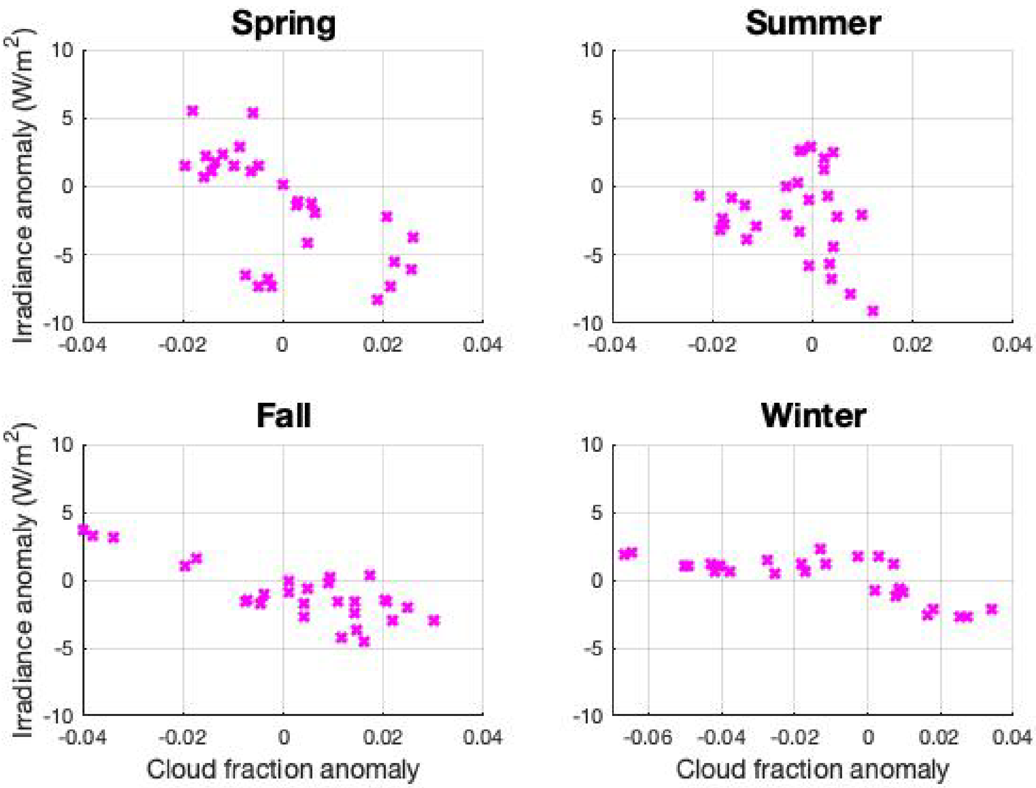

Figure 9 - Comparison between 11-year moving means of seasonal SSR anomalies and 11-year moving means of cloud fraction anomalies from ERA 5 at Piz Corvatsch.

The location of the station in the Southern Alps could be playing an important role for the differences observed in the long term all-sky SSR at Piz Corvatsch when compared to all the other stations analysed in this study. Panziera et al. (2015) have studied the regional circulation features at the region of Trentino (~60 km east of Piz Corvatsch, also in the Southeastern Alps). The authors highlighted the importance of the mesoscale mechanisms resulting from the interaction between large-scale flow with local orography to the atmospheric processes occurring in the region. One of the remarkable features highlighted by the authors regards the "shadowing" of the Trentino region by the western Alps in the occurrence of western flow, which is moist and usually associated with cloudiness in the western part of the Alps. This results in a more significant impact of the regional and local circulation patterns in the region, which might have contributed to the distinct long term SSR variability at Piz Corvatsch.

The lack of true overcast SSR data at this station does not allow for testing the hypothesis that changes in cloud optical depth could dominate the SSR variability at this site. But the comparison of the all-sky SSR time series at this station with the all-sky SSR behavior of the other Swiss stations already suggests that different processes dominate the SSR decadal trends at Piz Corvatsch, most likely with a major contribution of the changes in cloud cover. The role of cloud cover and cloud optical depth in the SSR trends, and potential causes for heterogeneity of the SSR trends in the Alpine region are discussed in the following section.

4 Discussion

The results presented here strongly suggest that changes in cloud optical depth play a major role in controlling SSR decadal trends at high altitude Alpine stations, whereas at low altitude stations, SSR trends are dominated by changes in the cloud-free atmosphere. Vienna is an exception to that, since changes in cloud cover dominate at this station. The conceptual framework on the role of aerosols and clouds in Global Dimming and Brightening (Wild, 2009) suggests that at pristine locations the indirect aerosol effect is of significant importance for the SSR trends, strongly affecting cloud optical depth and cloud lifetime. Such pristine conditions can be found at the high elevation sites analysed in this study. Due to their high elevations, they have a limited interaction with the lowest levels of the atmosphere, where the major anthropogenic pollution sources are located. This results in significantly lower AOD and particle number concentration at these high elevation sites than at the stations at lower altitudes. Consequently, one would expect that at high elevation sites reducing aerosols would lead to a positive forcing (brightening) primarily via aerosol indirect effect. This is supported by the absence of substantial clear-sky trends. The true overcast time series show in fact stronger positive trends in SSR at the high altitude stations in the end of the 20th century, consistent with the reported decline in sulfate aerosol loadings over Europe in that period (Stern, 2006). As observed, the higher average irradiance at higher altitudes also contributes to the higher absolute variability and stronger trends at these locations. Other aspects, however, could also affect the cloud optical depth, such as changes in cloud liquid water content, which were not assessed in this study. Thus, even though the results and the literature (e.g. Krüger and Graßl, 2002) point towards changes in cloud optical depth due to changes in aerosol loadings, we could not further challenge this hypothesis by comparing it to other potential causes for changes in cloud optical depth.

Saentis and Jungfraujoch show an especially interesting contrast between all-sky and clear-sky SSR trends. Those are the only two stations where a positive trend in clear-sky SSR was not observed at all. This is somewhat against an expected weak positive trend in clear-sky SSR, as observed (by both methods used for clear-sky derivation) in other Alpine stations (e.g. Weissfluhjoch, Guetsch-Andermatt, Piz Corvatsch), due to reducing aerosols. In the case of Jungfraujoch, observations even show a decrease in particle number concentration, in the end of the 20th century, which was not reflected in a positive clear-sky SSR trend. A potential cause for this persistent negative trend in clear-sky conditions at these stations could be associated with orographic forcing. Both are elevated peaks in the windside of the Alps from a synoptic point of view, as winds blow mostly from west in the region (Weber and Furger, 2001). Thus, orographic forcing mostly keeps a constant process of cloud formation, independent of the amount of moisture and CCNs present. For the case of Junfraujoch, Juranyi et al. (2011) have shown that cloud droplet activation is likely to occur in aerosol limited regime most of the time. Consequently, changes in aerosol loadings (more or less CCNs) would be reflected more in the aerosol indirect effect than in aerosol direct effect or in cloud cover changes. All the other high elevation stations do show some long term variability in the clear-sky SSR time series. But they are also located more in the inner Alpine areas (from the synoptic wind perspective), thus in more complex terrains when it comes to synoptic and local circulations.

Every station has its own local conditions, which makes it hard to understand every anomaly of every location. Especially at high altitude stations, local circulations features can significantly affect the decadal trends of SSR, but overall it is still possible to identify commonalities. The Swiss stations at all altitudes, with the exception of Piz Corvatsch, have a similar SSR long term variability, with all of them showing a brightening period starting between late 80s and late 90s. They are all located in the southwestern, western and northwestern parts of the Alps. The Austrian stations, located more in the eastern (inner) part of the Alps, also show a similar long term SSR variability between themselves, with positive trends, which change the sign around the turn of the century. Piz Corvatsch, located in southeastern Switzerland, in the southern part of the Alps, shows an unique long term SSR variability when compared to others. This leads us to identify three main general behaviors in the SSR decadal trends in the Alps: one in the western part, one in the eastern part and one in the southern part. Both western and eastern parts of the Alps show indications of similar main causes for long term trends in SSR: changes in cloud optical depth at high altitudes (with the exception of Col du Grand Saint Bernard, as previously mentioned) and in aerosol direct effect at low altitudes (with the exception of Vienna, as previously mentioned). However, the temporal variability in the forcings seems to be remarkably different from one to the other. In the southern part of the Alps (also an inner part from the synoptic wind perspective), at Piz Corvatsch, the available data implies a significant effect of cloud cover on the SSR variability and does not indicate major changes in cloud optical depth, although, a deeper analysis with more data would be required for testing this hypothesis.

Even though here we highlighted more the cloud optical depth effect on the SSR trends, the changes in cloud cover should also be considered, particularly when discussing inter-annual variations. Most sites show a very positive all-sky SSR anomaly in the year 2003, for example, which has been reported as an anomalous dry and hot year in Central Europe (Garcia-Herrera et al., 2010). So changes in cloud cover do affect inter annual variability at all stations, but the long term effects do not always play a major role for the SSR trends. This was observed for the case of Saentis, for example, which shows a stable cloud cover and relative humidity (not shown) on the long term from the 80s until most recent decades. However, it is very likely that any significant trends in cloud cover would dominate over any trends in cloud optical depth. Thus, we should highlight that the observed trends at high altitudes forced by changes in cloud optical depth occurred mostly without major cloud cover trends.

5 Conclusions

In this study we presented the SSR decadal trends at several stations, at low and high elevations, in and around the Swiss and Austrian Alps, and discussed their causes. The analysis of the time series available revealed a spatio-temporal heterogeneity in the SSR trends in the region. A remarkable spatial contrast between stations in the western, eastern and one station in the southern Alps could be identified, whereas stations within each of these regions had a similar general behavior in their long term trends. Further comparison between low elevation and high elevation sites revealed that at lower altitudes the SSR decadal trends were mostly determined by clear-sky processes, most likely related to the changes in aerosol loadings in the last two decades of the last century in Europe. An exception to that is Vienna, which shows strong decadal trends in cloud cover in line with SSR decadal trends. At high altitude sites, on the other hand, clear-sky trends accounted for a smaller portion of the total all-sky long term variability. After the identification of no major decadal changes in cloud cover in some sites, the analysis of the true overcast time series showed that changes in cloud optical depth play a major role for decadal SSR trends at high elevations. This could be associated with the aerosol indirect effect, as we can expect based on the particle number concentration time series at Jungfraujoch and on the conceptual framework on the role of aerosols and clouds in the Global Dimming and Brightening phenomenon (Wild, 2009). But, since we did not assess all aspects that could affect the cloud optical depth, additional analysis could still be performed to further test this hypothesis. We also observed that the cloud optical depth effect in SSR decadal trends at high altitude sites could be amplified by the fact that these sites have a smaller fraction of the atmosphere above them to attenuate radiation, resulting in higher average irradiance under true overcast conditions than those stations at lower altitudes. We further identified that changes in cloud cover still can play a role in all-sky SSR interannual variability, thus any long term trends in cloud cover could outweigh the cloud optical depth variability. This leads us to conclude that the cloud optical depth controls the decadal trends of SSR at high altitudes in the Alps as long as there are no major changes in cloud cover. The hypothesis that the changes in cloud optical depth in the Alps were caused mostly by the indirect aerosol effect should, however, still be subject of further research.

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Data Availability Statement

The BSRN SSR data is available at the BSRN website (https://bsrn.awi.de/). For this study it was retrieved via the ftp server ftp://ftp.bsrn.awi.de/. The WRDC SSR data is available for registered users at http://wrdc.mgo.rssi.ru/. The MeteoSwiss/IDAWEB SSR data is available for registered users at (https://gate.meteoswiss.ch/idaweb). Synop cloud cover and irradiance data from the European Climate Assessment & Dataset website can be downloaded at (http://www.ecad.eu). Synop cloud cover from Jungfraujoch was downloaded from Ogimet (https://www.ogimet.com/synops.phtml.en). Particle Number Concentration and Cloud Condensation Nuclei Number Concentration from Jungfraujoch were downloaded at the EBAS website (https://ebas-data.nilu.no/).

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