

# Trends in observed surface solar radiation and their causes in Brazil in the first two decades of the 21st century.

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**Abstract.** Numerous studies have investigated the long term variability of surface solar radiation (SSR) around the world. However, the large disparity in the availability of observational data between developed and least developed/developing countries leads to an underrepresentation of studies on SSR changes in the latter. This is especially true for South America, where few observational studies have investigated the SSR trends, and usually only at a local or regional scale. In this study we use data from 34 stations distributed throughout all the regions of Brazil to present the SSR trends in the first two decades of the 21st century and investigate their associated causes. The stations were grouped into 8 composites according to their proximity. Our results show that in the North and Northeast Brazil a strong dimming occurred, with significant contributions from increasing atmospheric absorption, most likely due to anthropogenic emissions, and increasing cloud cover. In the Southeast and Midwest regions of Brazil near-zero trends resulted from competing effects of clear-sky processes (attenuation of solar radiation under cloudless conditions) and strong negative trends in cloud cover. In the South part of the Amazon and in Southern Brazil a statistically insignificant brightening was observed, with significant contribution from decreasing biomass burning emissions in the former and competing minor contributions in the latter. These results can contribute to deepen the knowledge and understanding of SSR long-term trends and their causes in South America, reducing the underrepresentation of this continent when compared to regions like Europe.

## 1. Introduction

Decadal trends in surface solar radiation (SSR) have been the subject of study since pioneering studies in late 1980s and early 1990s made efforts to try to understand the long-term variation of SSR (Ohmura and Lang, 1989; Russak, 1990; Dutton et al., 1991; Stanhill and Moreshet, 1992). Several studies have followed presenting the trends and discussing their causes and potential consequences in several parts of the world (Wild, 2009), such as in Europe (e.g. Natsis et al., 2024; Kazadzis et al., 2018; Manara et al., 2016; Norris and Wild, 2007; Power, 2003), North America (e.g. Liepert 2002), China (e.g. Feng and Wang, 2019; Wang et al., 2015; Xia et al., 2007), Japan (e.g. Kudo et al., 2012) and New Zealand (Liley, 2009). Global dimming (negative trends in SSR) and brightening (positive trends in SSR) have been associated, in most of the cases, with changes in cloud cover (e.g. Stjern et al., 2008;

34 Augustine and Capotondi, 2022) and changes in aerosol loadings (e.g. Wild et al., 2021, Kambezidis et  
35 al., 2012), with the dominant aspect depending on regional atmospheric and emission features.  
36 However, many regions of the world are still underrepresented by such studies, mostly because of the  
37 lack of observational high quality data in most of developing and least developed countries in contrast  
38 to regions like Europe, North America or Eastern Asia. South America is an important region to be  
39 mentioned in this context.

40 The lack of long-term SSR data in South America, reported by different authors (Ohmura,  
41 2009; Gilgen et al., 2009), is the main cause for the absence of a long literature in the region. Still, a  
42 few studies tried to assess SSR variability in South America. Ohmura (2009) presented and discussed  
43 SSR decadal trends based on a few stations in Venezuela at the end of the 20th century. Schwartz (2005)  
44 used astronomical extinction measurements to estimate clear-sky SSR trends at one astronomical  
45 observatory in Chile during two decades (1978-1997). Yuan et al. (2021) and Jiao et al. (2023) used  
46 machine learning methods to spatially interpolate SSR ground observations and reanalysis data and  
47 used this approach to assess SSR decadal variability over the whole globe, including South America,  
48 covering the second half of the 20th century and the first two decades of the 21st century. Da Silva et  
49 al. (2010), de Jong et al. (2019) and de Lima et al. (2019) all assessed SSR variability in Brazil with a  
50 focus on the potential for photovoltaic energy production. Zuluaga et al. (2021) and Raichijk (2012)  
51 used sunshine duration to assess the SSR variability in Brazil for the last 2 to 4 decades of the 20th  
52 century and the beginning of the 21st century. A similarity between most of these studies is the fact that  
53 they had to rely on reanalysis, modeling data and indirect estimators of SSR (like sunshine duration),  
54 with the only of the abovementioned studies that used ground observations being limited to a small  
55 region in Venezuela. This leaves regions such as the densely populated southeastern Brazil or the highly  
56 climate-relevant Amazon region without any direct assessment of the regional SSR long term  
57 variability. Yamasoe et al. (2021) presented and discussed a SSR time series of fifty-six years (1961-  
58 2016) measured in the city of Sao Paulo, and that is, to our knowledge, the longest and most detailed  
59 analysis of directly observed SSR in South America. The studies referenced here apply different  
60 methods, to different regions, in different periods, so it is hard to directly compare them. But, in general  
61 terms, studies based on sunshine duration tend to indicate a brightening in Brazil after 1980s, while  
62 studies using machine learning techniques and regional observational studies show a spatial  
63 heterogeneity in the SSR trends in Brazil in the last few decades. All these studies provide different  
64 pieces of information about SSR variability in this part of the world, however, none of them provide a  
65 large scale assessment of the long term SSR decadal trends using ground observations of SSR, as done  
66 for regions like Europe (e.g. Chiacchio and Wild, 2010; Pfeifroth et al., 2018), China (e.g. Yang et al.,  
67 2018) or the United States (e.g. Long et al., 2009).

68 To try to tackle this gap in literature, we made use of the availability of SSR data from  
69 automated meteorological stations from the Instituto Brasileiro de Meteorologia (INMET) from 2001  
70 onwards to provide a large scale assessment of SSR decadal trends and underlying causes at the

71 beginning of the 21st century in the Brazilian territory, which covers approximately half of the South  
72 American continent. The direct assessment of SSR long-term variability (using observed SSR) over  
73 such a large area in South America represents a novel contribution from this work. The objective of this  
74 study is to present the in-situ observed SSR decadal trends around Brazil in the first two decades of the  
75 21st century and discuss their underlying causes. This is done at the regional level, rather than locally,  
76 by selecting stations in strategic locations around the Brazilian territory and grouping them into station  
77 composites. With this study we intend to help to reduce the under representativity of Global Dimming  
78 and Brightening (GDB) studies in South America.

## 79 **2. Data and methods**

### 80 **2.1 In situ SSR and cloud cover measurements**

81 Surface solar radiation data for 32 of the 34 stations (see table 3, in annex) is collected and  
82 controlled by the Instituto Nacional de Meteorologia (INMET) and was retrieved from the BDMEP  
83 portal (available at: <https://bdmep.inmet.gov.br/> (last access 27 Oct 2023)). The stations were chosen  
84 based on data availability in the regions of each composite used in this study (see section 2.4). The data  
85 was retrieved at hourly time resolution. All data was tested at the hourly time scale for consistency  
86 using the physical and extremely rare limits established by Long and Dutton (2002). None of the  
87 INMET stations used in this study were reported to have major discontinuities in the records.  
88 Nevertheless, we still applied the penalized maximal F test by Wang (2008) to verify the time series for  
89 inhomogeneities. No homogeneity problems were identified in the stations used in this study.

90 The hourly values were further converted into daily means by simply taking the average of the  
91 24 hourly values in a day. If one hourly value was missing (due to either lack of data or removal during  
92 quality test) the one hourly value was filled linearly using the previous and next hours and the daily  
93 value was the average of 24 hourly values (23 observed and 1 filled linearly). If more than one hourly  
94 value was missing, the daily value was not calculated. In this way, daily values were always the result  
95 of the average of 24 hourly values. Daily values were further converted into monthly values by simply  
96 averaging the daily means within the same month. Monthly values were only calculated when at least  
97 70% of the days in a month were available. For example, 70% of the days of any April are equivalent  
98 to 21 days. Therefore, if any April had 21 or more valid daily values, the monthly value would be  
99 calculated as the average of all available daily values. On the other hand, if less than 21 days had valid  
100 data, the monthly value would not be calculated. Further conversion from monthly to annual values  
101 again occurred by simply averaging the 12 months. If one, two or three monthly values went missing,  
102 the long term mean (mean for the whole period with available data) for that month would be used  
103 instead, and the annual mean was still calculated. If more than three monthly values were missing, then  
104 the annual value was not calculated. In this way, the annual value was always a result of 12 monthly  
105 values, from which no more than 3 were filled with the long term mean. The averaging procedure from

106 daily to monthly, and from monthly to annual values reproduces similar methodologies used in previous  
107 studies (e.g. Stjern et al., 2008; Manara et al., 2016).

108 The BSRN (Baseline Surface Radiation Network, Ohmura et al., 1998; Driemel et al., 2018)  
109 station at Florianopolis was also used in this study. Its data was provided at 15-minute intervals. Data  
110 from the station operated by the Instituto de Astronomia, Geofisica e Ciencias Atmosfericas of the  
111 Universidade de São Paulo (IAG/USP), located in the city of Sao Paulo was also used. Data from this  
112 station was provided as daily means. Both time series were also checked for consistency with the same  
113 procedure applied to the INMET stations, at the hourly time scale for the BSRN station and at the daily  
114 time scale for the IAG/USP station. Metadata for both stations did not report any discontinuities, and  
115 the tests performed using the penalized maximal F test by Wang (2008) also did not indicate any  
116 inhomogeneity in the time series. The SSR long term variability at the Sao Paulo station was previously  
117 carefully analyzed by Yamasoe et al. (2021). This station also has the longest time coverage among all  
118 of the stations used in this study: all the other stations only have data after 2000, while this stations has  
119 available data from decades earlier. But we limited the analysis to the period with coverage of the other  
120 stations because we intend to investigate the SSR variability at the regional level (composites) rather  
121 than at the local level (individual station). The procedure to convert from sub-daily to daily averages,  
122 from daily to monthly and from monthly to annual values at these two stations was the same as the  
123 procedure used for the INMET stations.

124 Cloud cover data was also retrieved through the BDMEP portal from the INMET. The stations  
125 were the same as used for the INMET SSR measurements with the addition of data from Florianopolis.  
126 In Florianopolis, where the SSR data is originally from BSRN, the location of the SSR and the cloud  
127 measurements differ by a few kilometers. Cloud cover data is collected from visual inspections at 00,  
128 12 and 18 UTC and is provided in units of tenths (1/10) of cloud cover.. The daily cloud cover values  
129 used in this study are a result of the average from the 12 and 18 UTC observations. This is equivalent  
130 to 9 and 15 local time at most of the stations used in this study (8 and 14 for the westernmost stations).  
131 At the Sao Paulo station, the diurnal cloud cover values are a result of hourly observations between 7  
132 and 18 local time. Cloud cover data was converted into monthly and then annual values using the same  
133 procedure as used for the SSR data. The cloud cover data is also used to calculate the Cloud Cover  
134 Radiative Effect (CCRE), following the procedure described by Norris and Wild (2007). This variable  
135 gives an estimation of the change in SSR produced by changes in cloud cover.

136 The SSR data described in this section is used to estimate the SSR trends presented in table 1,  
137 and to calculate the fractional atmospheric column absorption (see section 2.4), which also has the  
138 trends presented in table 1. The cloud cover data described in this section was used to estimate cloud  
139 cover trends presented in table 1 and to apply one of the two methods for clear-sky identification used  
140 in this study (see section 2.3).

## 141 **2.2 Satellite and reanalysis data**



142 To investigate Aerosol Optical Depth (AOD) variability, we used data from the CAMS  
143 (Copernicus Atmosphere Monitoring System) reanalysis (Inness et al., 2019), provided by ECMWF.  
144 This product has monthly time steps and spatial resolution of approximately 80 km, with temporal  
145 coverage starting from 2003. Gueymard and Yang (2020) validated CAMS data using AERONET  
146 stations from around the world, including South America and found that the reanalysis performs well  
147 in comparison to in-situ aerosol observations, therefore being well suited for regional and global studies.  
148 To assess the Aerosol Absorption Optical Depth (AAOD) at 500 nm we used data from the OMAERUV  
149 aerosol algorithm from the Ozone Monitoring Instrument (OMI, Torres et al., 2007). The product is  
150 provided at daily time resolution and 1-degree resolution, and is available from 2004 onwards. Due to  
151 the frequent occurrence of missing daily values in the AAOD data from OMI (due to different aspects,  
152 such as cloudy scenes), conversion from daily to monthly values was done only when at least two days  
153 in a month were available. From monthly to annual values the conversion was only performed when at  
154 least 11 of the 12 months had available data (missing month would be filled with long term mean, that  
155 is, the mean for the whole period with data availability). We should also highlight that aerosol  
156 absorption is a variable highly dependent on the spectral region, thus the absorption at 500 nm could  
157 not be representative for the whole spectrum.

158 We also used shortwave radiative fluxes measured at the Top of the Atmosphere (TOA) by the  
159 CERES (Cloud and Earth's Radiant Energy System, Doelling et al., 2013) instruments on board of the  
160 satellites Terra and Aqua. The CERES-SSF product (Doelling et al., 2016), used in this study, provided  
161 TOA shortwave fluxes at monthly time intervals and 1-degree spatial resolution, from 2000 onwards.  
162 The same product also provided incoming shortwave radiative fluxes at the TOA, which was also used  
163 in this study. The data from CERES was used to estimate fractional atmospheric column absorption  
164 (see section 2.4).

165 Anthropogenic emissions were assessed using EDGAR (Emissions Database for Global  
166 Atmospheric Research, Crippa et al., 2018). The data provides anthropogenic emission estimates at 0.1  
167 degree spatial resolution and does not consider large scale biomass burning, land use change and  
168 forestry (Crippa et al., 2018). This dataset was used, even though it does not include biomass burning,  
169 because it provides information about aerosol emissions from all other sources, which are also relevant,  
170 such as urban and industrial emissions. For this study we acquired the data in annual values and in units  
171 of  $\text{kg m}^{-1} \text{s}^{-1}$ . The unit was further converted to  $\text{kg grid}^{-1} \text{year}^{-1}$  (kg emitted for each 0.1 degree grid per  
172 year). Finally, total column water vapour was obtained from the ERA5 reanalysis (Hersbach et al.,  
173 2020), which provides data with a 0.25 degree spatial resolution and monthly time resolution. Cloud  
174 cover from ERA5 was also used as supporting information in addition to the previously mentioned  
175 SYNOP cloud cover, measured in-situ.

176 The AOD, AAOD, water vapor and anthropogenic emissions data described in this section were  
177 used to identify the spatial distribution of the trends for these variables. The TOA incoming and  
178 outgoing irradiance data described in this section was used to estimate fractional atmospheric column

179 absorption (see section 2.4). For all gridded data described in this section, the stations were sampled by  
180 taking the grid box containing the station coordinates.

181

### 182 **2.3 Clear-sky SSR**

183 Time series of clear-sky SSR were derived using two different methods. At all stations we used  
184 (1) the clear-sky method proposed by Correa et al. (2022), and at the stations with Synop cloud cover  
185 data we also (2) derived clear-sky using cloud cover information. We applied both methods on the daily  
186 time series. For the first method, we calculate station specific daily transmittance thresholds for every  
187 month of the year. Days with transmittance lower than this threshold for the specific station in the  
188 respective month are flagged as cloudy and removed. Days with transmittance above the thresholds are  
189 flagged as clear-sky. As this method relies on the reduction of atmospheric transmittance under cloudy  
190 conditions, its main weakness is associated with extreme aerosol events that could suddenly strongly  
191 reduce transmittance. Thus this method is not well suited for the analysis of high frequency (interannual)  
192 variability, but it has been shown adequate for assessment of long term trends (Correa et al., 2022).

193 For the second method, we simply used in-situ observations of cloud cover to identify cloudy  
194 scenes. We set the threshold of cloud cover to two tenths (20%), where any day with cloud cover above  
195 that was flagged as cloudy and removed. The choice of the cloud cover threshold represents a trade-off,  
196 where low thresholds (say, 0%) would completely avoid any cloud signal but would also remove days  
197 with low cloud occurrence, where the effects of cloud-free processes still dominate, and leave the time  
198 series with very few valid values. For this reason, we allowed a higher threshold, assuming that on days  
199 with such low cloud cover (0-20%) the cloud-free processes still dominate the signal of the SSR  
200 variability.

201 In both methods, the removal of cloudy days results in clear-sky SSR time series with many  
202 gaps. Thus, special care should be taken when converting from daily to monthly values and from  
203 monthly to annual values. Monthly values were only calculated when at least two daily values were  
204 available for the respective month. But before taking their average, each available daily value is  
205 normalized to the 15th day of the month by multiplying the daily irradiance with a normalization factor.  
206 This normalization factor is a result of the ratio between the TOA daily irradiance at the 15th day of the  
207 month and at the day flagged as clear-sky. This is done to correct for the solar geometry at different  
208 times of the month. From monthly to annual values the procedure is the same as done for all-sky SSR:  
209 the calculation is done when at least 10 months are available, with missing values being replaced by  
210 long term means. When less than 10 months are available, the annual means are not calculated.

211

### 212 **2.4 Fractional atmospheric column absorption**

213 The daily fractional atmospheric column absorption ( $F_{abs}$ ) was calculated for every station by  
 214 combining SSR measured at the surface, surface albedo from ERA5 at the 0.25x0.25 degree spatial  
 215 resolution and incoming and outgoing shortwave radiation at TOA from CERES-SSF 1deg from the  
 216 Terra satellite (1x1 degree spatial resolution) and daily time resolution. For the gridded data the pixel  
 217 containing the station coordinates was used. These variables were combined in equation 1 to calculate  
 218  $F_{abs}$ .

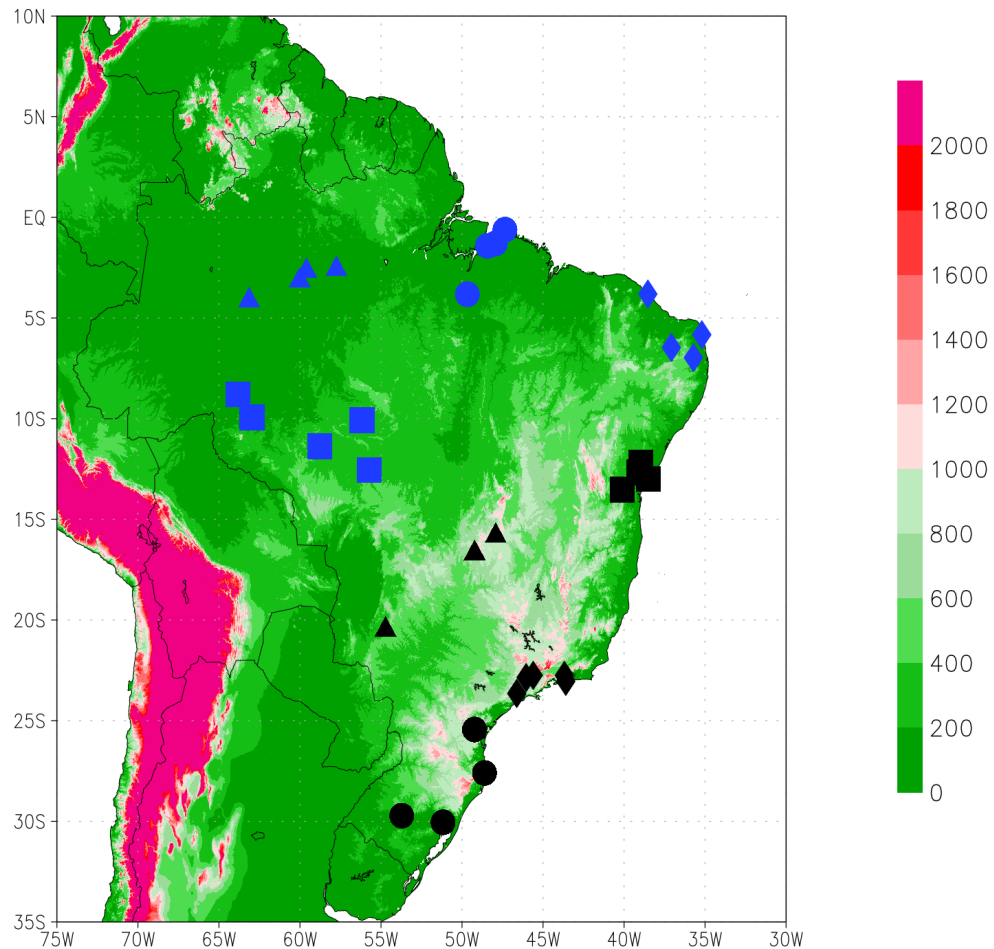
$$219 \quad F_{abs} = 1 - (SW_{upTOA}/SW_{downTOA}) - ((1-\text{albedo}_{SFC}) * (SW_{downSFC}/SW_{downTOA})) \quad (1)$$

220  $SW_{upTOA}$  is the outgoing shortwave radiation at TOA,  $SW_{downTOA}$  is the incoming shortwave  
 221 radiation at TOA,  $\text{albedo}_{SFC}$  is the surface albedo and  $SW_{downSFC}$  is the SSR. Thus, the term  
 222  $(SW_{upTOA}/SW_{downTOA})$  represents the fraction (0-1) of the incoming shortwave radiation at the TOA  
 223 which is reflected back to space, and the term  $((1-\text{albedo}_{SFC}) * (SW_{downSFC}/SW_{downTOA}))$  represents the  
 224 fraction (0-1) of the incoming shortwave radiation at the TOA which is absorbed at the surface. Then,  
 225  $F_{abs}$  represent the fraction of the incoming shortwave radiation at TOA which is absorbed within the  
 226 atmosphere column.  $F_{abs}$  values can range between 0 and 1, where 0 would represent no atmospheric  
 227 absorption and 1 would represent a black body absorption by the atmosphere.

228

## 229 **2.5 Selection of station composites**

230 The stations used in this study were divided into eight composites based on geographical  
 231 proximity, demographics and atmospheric features found in Brazil. That is, the composites were  
 232 organized with the intent of covering different climate characteristics around the country and, in most  
 233 cases, included data from big cities (> 1 million inhabitants). The use of data from big cities facilitates  
 234 the construction of the composite time series, since the stations with longest time series and less missing  
 235 data were found near big centers. The composites are: [1] Manaus region, [2] Belem region, [3]  
 236 Fortaleza region, [4] Salvador region, [5] South Amazon, [6] Midwest Brazil, [7] Southeast Brazil and  
 237 [8] South Brazil. The location of all stations are shown in Figure 1, and colors and markers denote the  
 238 different composites. Each composite is composed of three to five stations. Based on literature review,  
 239 Reboita et al. (2010) divided the precipitation regimes in South America in 8 regions, out of which five  
 240 regions are in the Brazilian territory. Ferreira and Reboita (2022) revisited the topic and applied a non-  
 241 hierarchical clustering technique to classify the precipitation regimes in South America. The authors  
 242 also found 8 different precipitation regimes in the continent and only minor spatial differences to the  
 243 previous study, with five of the regimes being present in the Brazilian territory. All of them were at  
 244 least partly represented by the composites.



245  
 246 **Figure 1: Map of Surface Solar Radiation stations and composites used in this study and topography of**  
 247 **South America (in meters above sea level). Colors and shapes represent the different composites: Blue**  
 248 **triangles = Manaus region; Blue circles = Belem region; Blue diamonds = Fortaleza region; Black squares**  
 249 **= Salvador region; Blue squares = South Amazon; Black triangles = Midwest Brazil; Black diamonds =**  
 250 **Southeast Brazil; Black circles = South Brazil.**

251 In the north of Brazil two composites were centered around the two biggest cities in the  
 252 Brazilian Amazon, (1) Manaus and (2) Belem. Precipitation and cloudiness in both regions is strongly  
 253 tied to local to mesoscale phenomena, like local convection, sea breeze circulation and squall lines. At  
 254 the large scale, the Intertropical Convergence Zone (ITCZ) also has a significant influence on the  
 255 precipitation in the regions, playing a major role for the seasonality of precipitation (Fisch et al., 1998).  
 256 Feedbacks with the Amazon rainforest are also important, especially the recycling of precipitation. But  
 257 regarding biomass burning in the Amazon, the most important area is located in the southern part of the  
 258 Amazon (Artaxo et al., 2006), south of both Belem and Manaus. The occurrence of the South American  
 259 Low Level Jet (Vera et al., 2006), important for moisture and aerosol transport from the Amazon to  
 260 Southeastern Brazil, leaves the locations of Belem and Manaus with lower influence of biomass burning  
 261 aerosols than the southern fraction of the Amazon. Still, the influence of aerosols from the forests (either

262 biogenic or biomass burning related) should not be neglected (Rosario et al., 2019), and most  
263 importantly, the importance of anthropogenic emissions from such big population centers should be  
264 taken into account.

265 In the northeast of Brazil, the composites of (3) Fortaleza and (4) Salvador share similar general  
266 characteristics regarding precipitation and cloudiness regimes. The stations in these composites are also  
267 centered around big population centers (Fortaleza and Salvador), where anthropogenic emissions  
268 should be taken into account. The biggest difference to the composites around Manaus and Belem, is  
269 that these two composites are not located in the Amazon region. But they are located in the same  
270 precipitation regime division proposed by by Ferreira and Reboita (2022), with two stations of the  
271 Fortaleza composite being located in a different subdivision.

272 The composite (5), South Amazon, was chosen to cover the region under the strongest influence  
273 of biomass burning aerosols from the Amazon (Artaxo et al., 2006). The stations in this composite are  
274 located in a different subdivision by Ferreira and Reboita (2022), where large scale phenomena (such  
275 as the Bolivian high, the South Atlantic Convergence Zone and cold fronts) play an important role for  
276 the cloud formation. This composite is not centered around a big city, and the most populated city in  
277 the area is Porto Velho, with a population of approximately 500'000 people (IBGE, 2022). A few  
278 degrees south of the South Amazon composite, are the stations of the (6) Middle West Brazil composite.  
279 They are located approximately halfway between the South Amazon composite and the densely  
280 populated Southeast Brazil. It is a dry region mostly influenced by large scale phenomena, compared  
281 to the north and northeast regions of Brazil. The biggest city in the composite is Brasilia.

282 The Southeast is the most densely populated area in Brazil, where big centers like Sao Paulo  
283 and Rio de Janeiro are located. Like the Middle West and South Amazon composites, cloud formation  
284 in this region is mostly associated with large scale phenomena, with significant influence from local  
285 convection and sea breeze being limited mostly to summer months (Reboita et al., 2010; Ferreira and  
286 Reboita, 2022). The (7) Southeast Brazil composite covers this area. The transport of humidity and  
287 aerosols from the south Amazon are both relevant aspects to consider. But regarding aerosols, urban-  
288 industrial emissions from the large population centers should be more relevant. The last station  
289 composite covers the Southernmost part of the country. The (8) South Brazil composite is entirely  
290 located in subtropical latitudes, and covers its own precipitation regime subdivision from Ferreira and  
291 Reboita (2022). Large scale phenomena like frontal systems and extra-tropical cyclones play a major  
292 role for cloud formation and moisture transport from the ocean. It is also a densely populated region,  
293 with big cities like Porto Alegre, Curitiba and Florianopolis, thus, urban-industrial aerosol emissions  
294 should be taken into account.

295 The whole discussion in this study revolves around these eight composites. Each variable was  
296 fully processed and converted to annual values at the station level, and only after that, they were grouped  
297 with the other stations in the respective composite. The list of stations in each composite can be found  
298 in Table 3 (in appendix).

## 299           **2.6 Trend calculations**

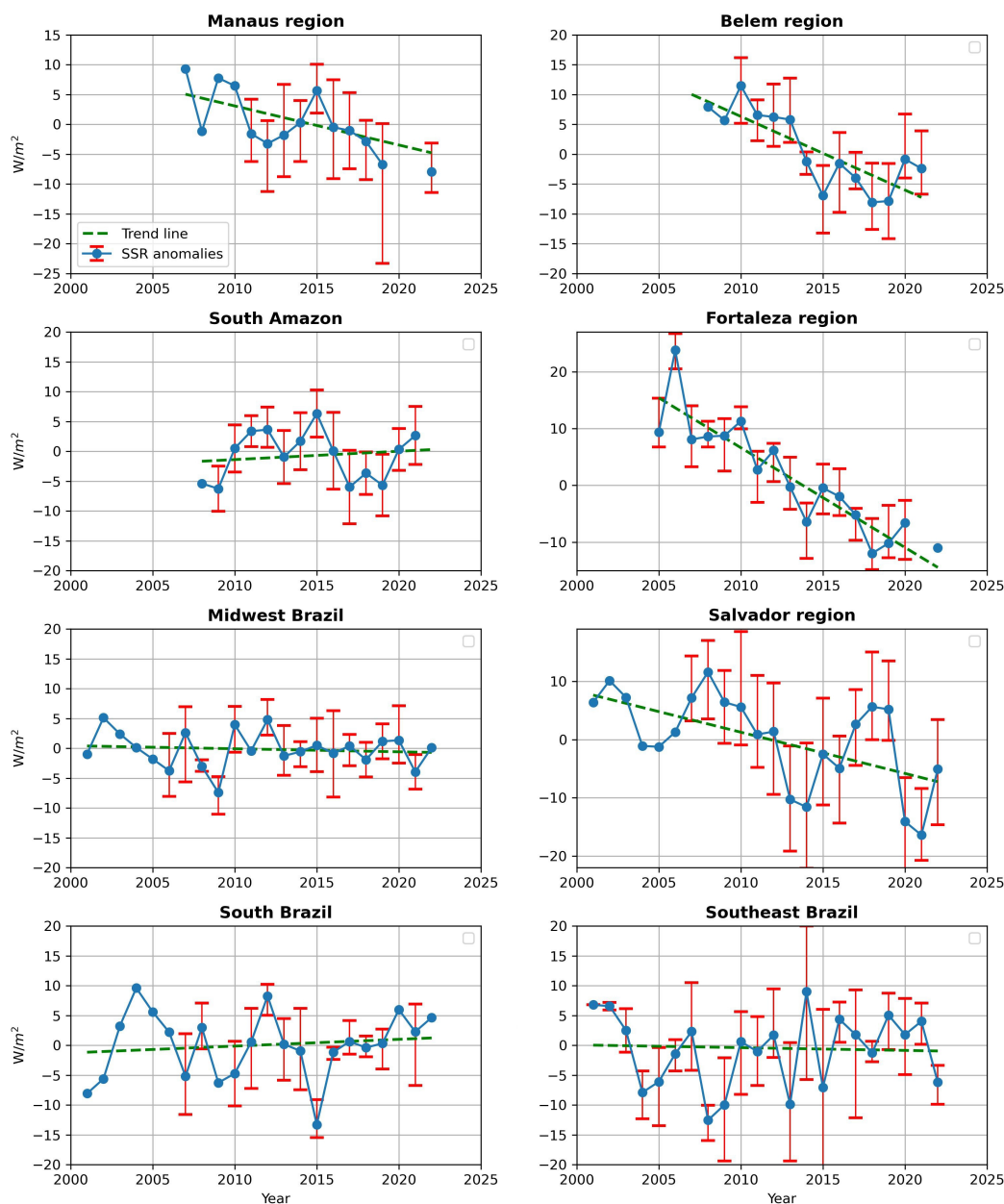
300           The trend analysis was based on annual anomalies of SSR. To calculate the annual anomalies,  
301 the absolute SSR annual values were subtracted from the average SSR value for the whole period of  
302 data availability for the respective composite (see table 1). This did not affect the trends, but facilitated  
303 the visualization and comparison between time series, since the anomalies are centered around a  
304 common value (zero). Decadal trends of SSR and most other variables presented in this study were  
305 calculated using a Linear Least Squares (LLS) regression, with the confidence intervals (at the 95%  
306 confidence level) being calculated using equation 4 from Nishizawa and Yoden (2005). Cloud cover  
307 time series, in most cases, did not have the residuals normally distributed, thus, to account for that, we  
308 calculated their trends using the Sen's slope (Sen, 1968) and Mann-Kendall test (Mann, 1945; Kendall,  
309 1975). Trends of ground observations were calculated for the whole time availability of the composites,  
310 however, as the time availability varies from one composite to the other, the periods used for trend  
311 calculations vary by a few years. SSR trends are displayed in units of  $W/m^2$  per decade. The period  
312 considered in each composite is displayed in Table 1.

313

## 314           **3. Results**

### 315           **3.1 All-sky and clear-sky SSR trends**

316           Figure 2 shows the all-sky SSR anomalies time series of the 8 composites analyzed in this  
317 study. All trends calculated in this study are shown in Table 1.



318

319 **Figure 2: Time series of all-sky Surface Solar Radiation annual anomalies from the eight composites used**  
 320 **in this study. Each composite is composed of three to five stations. In each composite, anomalies are with**  
 321 **respect to the mean of the entire period (shown in table 1). The error bars indicate the maximum and**  
 322 **minimum value for the individual stations in the respective year and composite. Trends are indicated by**  
 323 **dashed lines.**

324

325

Composites	Period	All-sky	Clear-sky (Correa et al., 2022)	Clear-sky (Synop)*	Synop Cloud cover	All-sky atm abs	Clear-sky atm abs	CCRE
Manaus region	2007-2022	<b>-8.8 ± 4.2</b>	-2.0 ± 2.3	-	<b>1.2 [0.0; 2.0]</b>	<b>0.021 ± 0.007</b>	0.005 ± 0.007	-1.1

Belem region	2008-2021	<b>-11.7 ± 5.8</b>	<b>-4.8 ± 2.5</b>	-	<b>1.4 [0.4; 1.3]</b>	<b>0.016 ± 0.010</b>	-0.001 ± 0.006	-1.5
Fortaleza region	2005-2022	<b>-16.0 ± 4.2</b>	<b>-2.7 ± 1.8</b>	-	0.8 [-1.3; 2.5]	<b>0.034 ± 0.012</b>	0.003 ± 0.011	-0.4
Salvador region	2001-2022	<b>-7.0 ± 4.5</b>	<b>-3.7 ± 1.7</b>	-	<b>1.9 [0.7; 3.1]</b>	<b>0.016 ± 0.008</b>	<b>0.010 ± 0.006</b>	-1.3
South Amazon	2008-2021	0.8 ± 6.4	1.6 ± 1.8	-	-	0.005 ± 0.015	-0.003 ± 0.007	-
Midwest Brazil	2001-2022	-0.4 ± 2.1	<b>-1.8 ± 1.1</b>	<b>-2.5 ± 1.9</b>	<b>-1.3 [-2.1; -0.3]</b>	<b>0.005 ± 0.003</b>	<b>0.005 ± 0.005</b>	1.4
Southeast Brazil	2001-2022	-0.1 ± 4.5	-1.6 ± 1.9	-7.7 ± 8.5	<b>-3.7 [-5.5; -1.3]</b>	0.002 ± 0.006	0.006 ± 0.007	3.9
South Brazil	2001-2022	2.0 ± 3.8	1.1 ± 4.1	1.2 ± 1.9	-0.2 [-1.3; 0.7]	0.001 ± 0.005	-0.003 ± 0.007	0.2

326

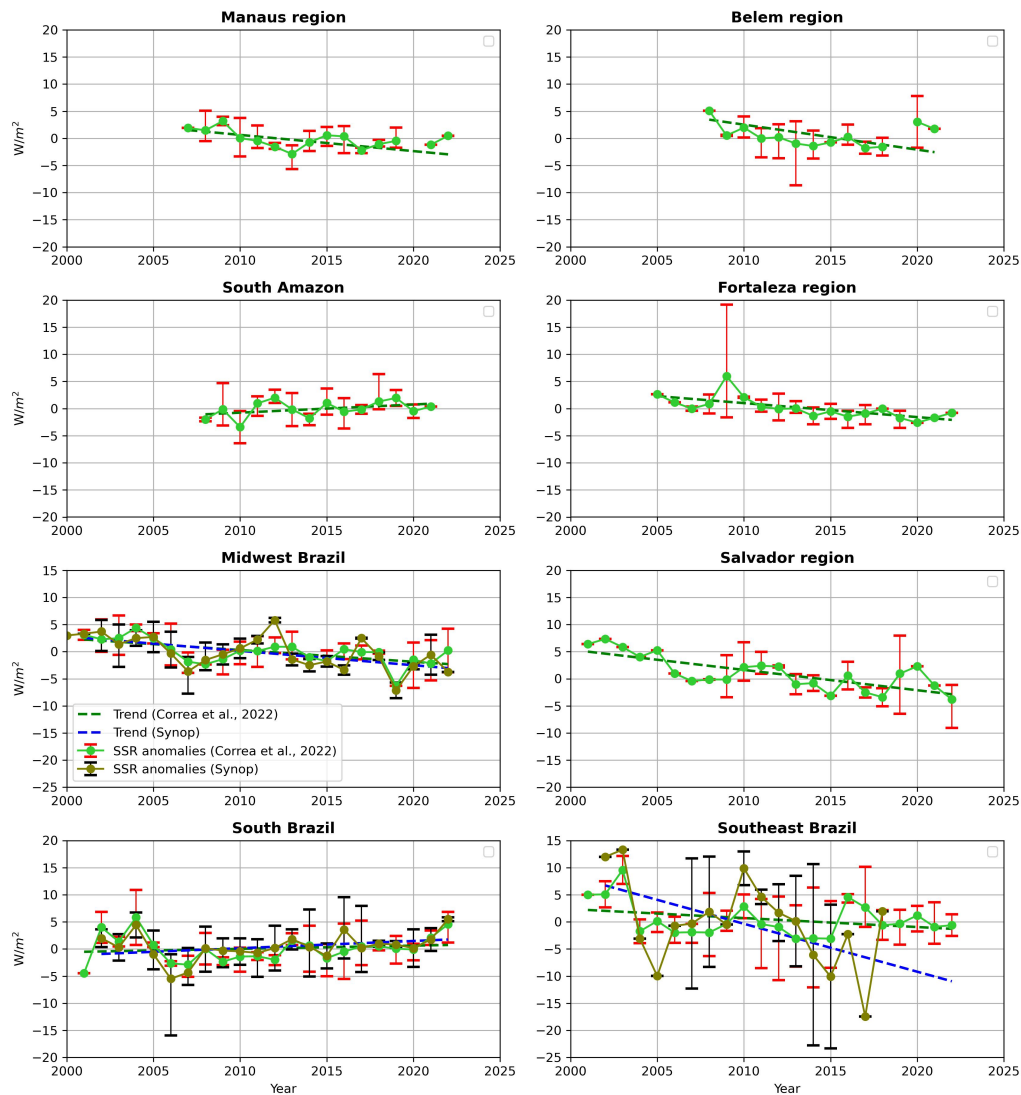
327

328 **Table 1 - Trends (in W/m<sup>2</sup> per decade) for all-sky and clear-sky (using Correa et al., 2022, and using Synop**  
329 **cloud cover) SSR, all-sky and clear-sky (using Correa et al., 2022) fractional atmospheric absorption and**  
330 **Synop cloud cover at the 8 composites used in this study. Cloud Cover Radiative Effect (CCRE) referring**  
331 **to the Synop cloud cover trend also included - this is an estimate of the effect on SSR of the cloud cover**  
332 **changes. SSR trends in W/m<sup>2</sup> per decade; fractional atmospheric absorption trends in fraction (values**  
333 **between 0 and 1) per decade; Synop cloud cover in % per decade; and CCRE in W/m<sup>2</sup>. Trends in bold are**  
334 **statistically significant at the 95% confidence level. Trends for Synop cloud cover were calculated using the**  
335 **Mann-Kendall test (see section 2.6), and as a result, the confidence interval is not always symmetrical. For**  
336 **this reason the confidence interval is shown in square brackets., Stations in each composite are listed in**  
337 **Table 3 (in appendix).**

338 **\*Missing values for clear-sky Synop trends occur due to the limited amount of Synop cloud cover data (0**  
339 **stations for the South Amazon composite, 2 out of 4 stations for Belem and Manaus composites) or due to**  
340 **not enough days flagged as clear-sky in order to generate a clear-sky time series (according to the procedure**  
341 **described in section 2.3).**

342 The period covered by the data in this study should always be kept in mind, as it is shorter than  
343 long-term studies of SSR trends in regions like Europe, North America and China. However, this  
344 timespan should be enough to start identifying the relevant features affecting SSR on timescales of a  
345 decade and beyond. In the North and Northeast Brazil composites (Belem, Manaus, Fortaleza and  
346 Salvador) statistically significant (at the 95% confidence level) negative SSR trends (dimming) were  
347 observed. In the Southeast and Middle West composites, trends were negative, although near zero and  
348 statistically insignificant. Southern Amazon and South Brazil composites both show statistically  
349 insignificant positive SSR trends (brightening). This reveals a contrasting spatial distribution of the all-  
350 sky SSR trends in the first two decades of the 21st century in Brazil: while strong dimming occurred in  
351 the northern half of the Amazon region and in the northeastern coastal region, near-zero to weak positive  
352 SSR trends occurred from the southern part of the Amazon down to the south of Brazil, including the  
353 central area of the country and the densely populated southeastern region. Figure 3 shows the time series  
354 of clear-sky SSR derived with the two methods used in the study.





355  
 356 **Figure 3: Time series of clear-sky Surface Solar Radiation annual anomalies (with respect to the composite**  
 357 **full time coverage, shown in Table 1) from the eight composites used in this study. Light green time series**  
 358 **derived using the method by Correa et al. (2022) and olive green time series derived using Synop cloud**  
 359 **cover to identify clear-skies. The error bars indicate the maximum and minimum value for the individual**  
 360 **stations in the respective year and composite. Trends are indicated by dashed lines.**

361 Time series of clear-sky SSR based on synop cloud cover could not be derived in five out of  
 362 the eight composites (see figure 3 and table 1). Synop clear-sky time series were derived when at least  
 363 three stations in the composite had clear-sky data (see availability in table 3). The Manaus, Belem and  
 364 South Amazon composites did not fulfill this requirement. For both Fortaleza and Salvador region  
 365 composites, Synop cloud cover data was available for all stations, however, the few occurrences  
 366 of low cloud cover days did not enable the derivation of clear-sky SSR time series  
 367 following the procedure described in section 2.3.

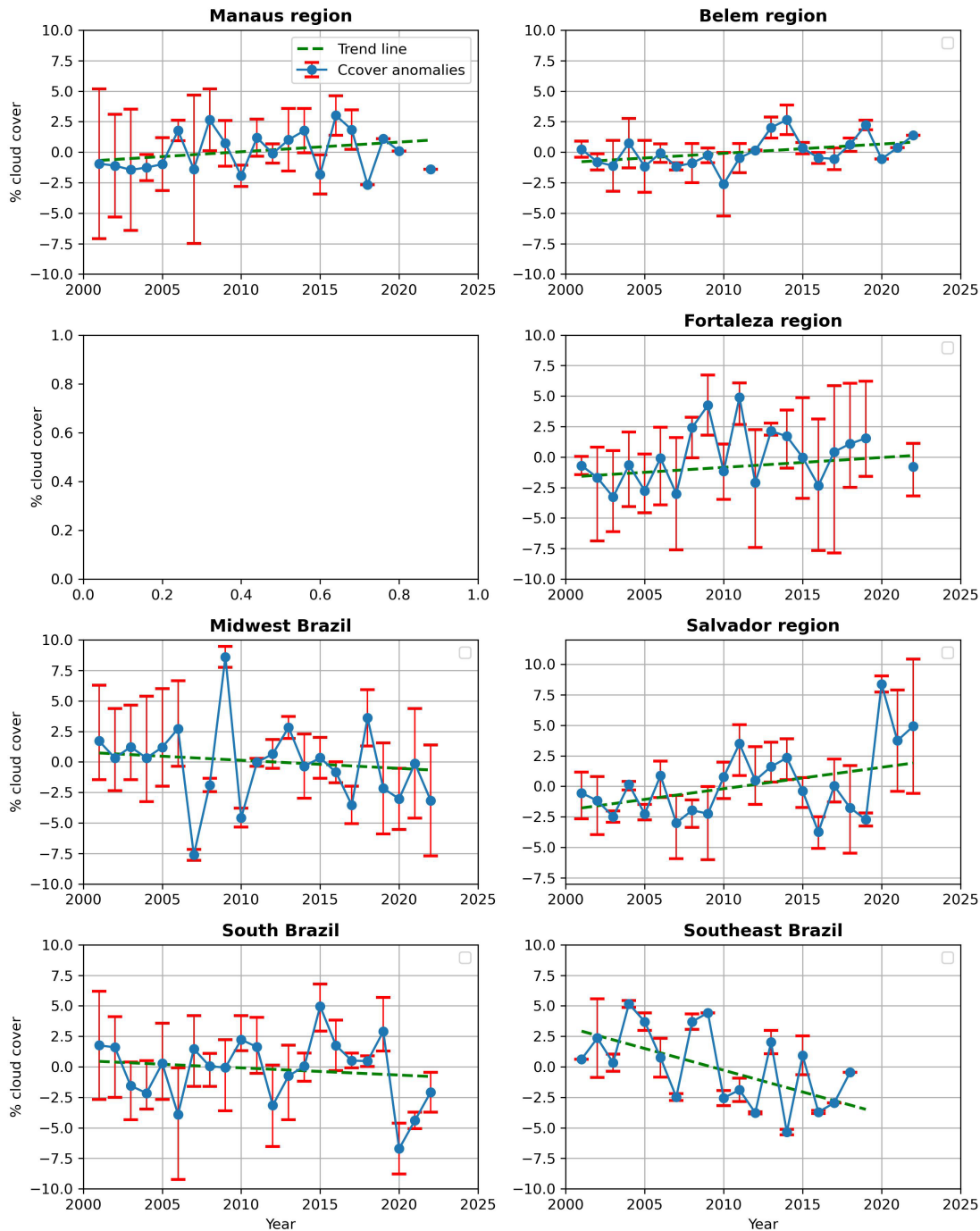
368 Clear-sky SSR time series show in general a similar pattern as observed in all-sky. All of the  
 369 composites show the same sign as the trends in all-sky, and six of them also indicate the same statistical  
 370 significance (or insignificance). The only exceptions are the Midwest and Manaus composites. The  
 371 former showed statistically insignificant negative trends in all-sky SSR, but statistically significant

372 negative clear-sky SSR trends. The opposite occurred in the Manaus composite: statistically significant  
373 all-sky SSR trends and statistically insignificant clear-sky SSR trends. For the composites where clear-  
374 sky data could be derived with both methods, in two of them (South and Midwest Brazil) both methods  
375 indicate very similar inter annual variability and trends, while in the other (Southeast Brazil) the two  
376 methods do not show strong agreement in the inter annual variability, but agreed in the direction of the  
377 trend. Therefore, the results of the clear-sky SSR trends are supported by both clear-sky methods.  
378 Regarding the magnitudes of the clear-sky SSR trends in comparison to the all-sky trends, another  
379 general pattern could be observed. In all composites with statistically significant negative all-sky SSR  
380 trends (Belem, Manaus, Fortaleza and Salvador), the clear-sky SSR trends showed a substantially  
381 smaller magnitude. In the Southeast and Middle West, both with near-zero all-sky SSR trends, the clear-  
382 sky SSR trends were both negative and of larger magnitude than their all-sky counterparts. In the two  
383 composites with observed statistically insignificant all-sky SSR brightening (South Amazon and South  
384 Brazil), the clear-sky SSR trends showed similar magnitudes as the all-sky SSR trends.

385         These results indicate that the clear-sky processes in the atmosphere contributed to the observed  
386 all-sky SSR trends in the whole of Brazil, but only in the Southern Amazon and in South Brazil their  
387 magnitude might have been large enough to be able to explain the observed SSR trends. “Clear-sky  
388 processes” in this context refers to the interaction between solar radiation and the components of the  
389 atmosphere without the presence of clouds. Further analysis is thus needed to better understand the  
390 reasons for the clear-sky and all-sky decadal SSR trends observed in Brazil.

### 391 **3.2 Cloud cover, AOD and water vapour trends**

392         Clouds, aerosols and water vapour all can attenuate solar radiation, therefore, their variability  
393 is analyzed in more details in this section. The order in which they are mentioned follow the order of  
394 relevance in the discussion of solar radiation attenuation in the atmosphere, with clouds being the most  
395 important aspect and water vapour the least important aspect. Figure 4 shows the SYNOP cloud cover  
396 time series for 7 of the 8 composites analyzed in the study (the cloud cover time series for the Southern  
397 Amazon composite could not be constructed due to too much missing data). The associated trends can  
398 be found in Table 1.



399

400

401 **Figure 4 - Time series of annual mean Synop cloud cover anomalies for seven of the eight composites used**  
 402 **in this study. Not enough data was available to derive a time series for the South Amazon composite. The**  
 403 **error bars indicate the maximum and minimum value for the individual stations in the respective year and**  
 404 **composite. Trends are indicated by dashed lines.**

404

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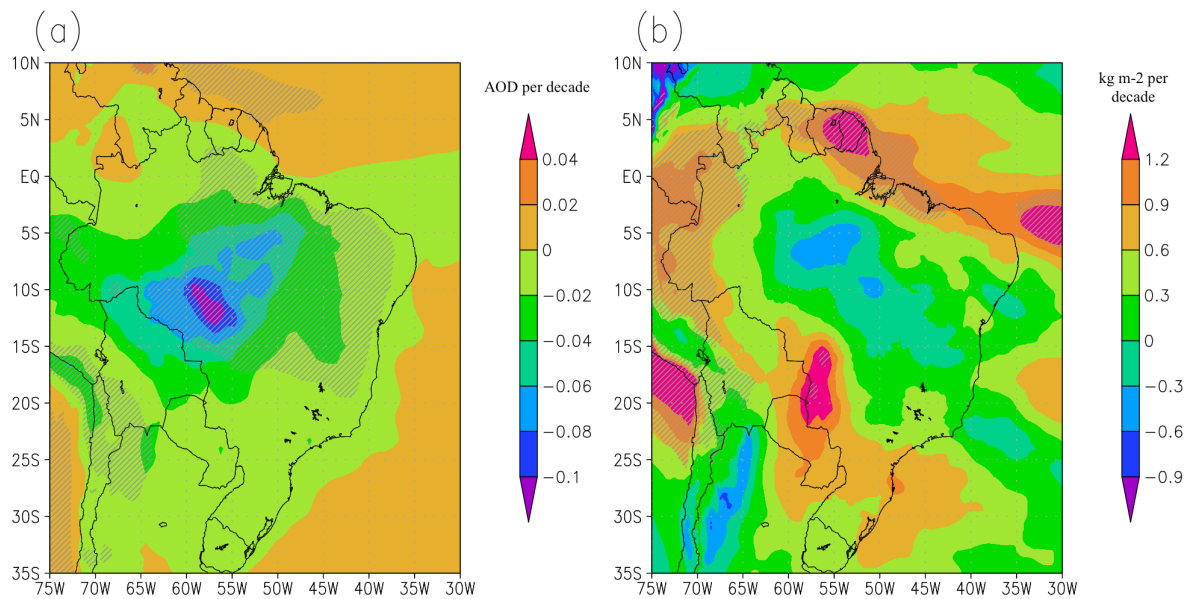
The Manaus, Belem and Southeast Brazil composites do not have synop cloud cover data for all stations (2 out of 4 available for Manaus and Belem, and 3 out of 5 for Southeast Brazil), therefore a comparison between all-sky SSR trends and Synop cloud cover at these composites is based on the assumption that the cloud cover observations for the composites are representative for all stations. This is a reasonable assumption given the geographical proximity between the stations within these three composites and the lack of any climatic or geographical feature that can strongly affect cloudiness at

410 individual stations (e.g. high topography). In these composites, all stations are located in areas with the  
411 same precipitation regimes as classified by Ferreira and Reboita (2022), also corroborating with the  
412 assumption of good representativeness.

413 Cloud cover trends are in most cases consistent in sign with the all-sky SSR trends. That is,  
414 positive (negative) trends in cloud cover occurring during a period of negative (positive) SSR trends.  
415 That is the case for the four composites with statistically significant all-sky SSR dimming (Belem,  
416 Manaus, Fortaleza and Salvador). They all show positive trends in cloud cover, and all, except  
417 Fortaleza, show statistical significance. This is consistent in the sense that the increase in cloud cover  
418 contributes to the observed decrease in SSR, especially considering that the magnitude of the clear-sky  
419 SSR trends at these locations was significantly smaller than the all-sky SSR trends. However,  
420 quantitatively, the small magnitude of the cloud cover trends (between 0.8 and 1.9 % per decade)  
421 challenges any hypothesis of a major contribution of cloud cover changes to the decadal SSR trends.  
422 That is, the cloud cover trends are too small and, as a consequence, the contribution of changes in  
423 cloud cover to the SSR trends is expected to be minor. This contribution is estimated objectively by the  
424 CCRE (see table 1), which shows, in most cases, low values (in comparison to the all-sky SSR trends),  
425 suggesting only a minor contribution from cloudiness to the SSR trends.

426 Cloud cover trends show near-zero values in the South region, suggesting no major cloud cover  
427 contribution to the SSR trends. Southeast and Middle West show both statistically significant negative  
428 trends in cloud cover, with remarkably strong values in SE (-3.7 [-5.5; -1.3] % per decade). Both  
429 composites show near-zero but negative all-sky SSR trends, with stronger negative clear-sky SSR  
430 trends. Thus, the cloud cover trends exert an opposite effect to the one of the clear-sky processes at both  
431 composites. This is also consistent, in the sense that with clear-sky processes and cloud cover having  
432 competing opposite effects, if their magnitude is similar, their effects cancel out, and the resulting all-  
433 sky SSR trend would be near zero.

434 Figure 5 shows the decadal trend maps of annual AOD in the 2003-2020 period from CAMS  
435 reanalysis and of total column water vapour in the 2001-2020 period from ERA5.



436  
 437 **Figure 5 - Maps of decadal trends of (a) AOD [unitless] in the 2003-2020\* period from CAMS reanalysis**  
 438 **and of (b) total column water vapour [in kg m<sup>-2</sup>] in the 2001-2020 period from ERA5. Shaded areas indicate**  
 439 **statistical significance (at the 95% confidence level).**  
 440 **\*The dataset was available only from 2003 onwards.**

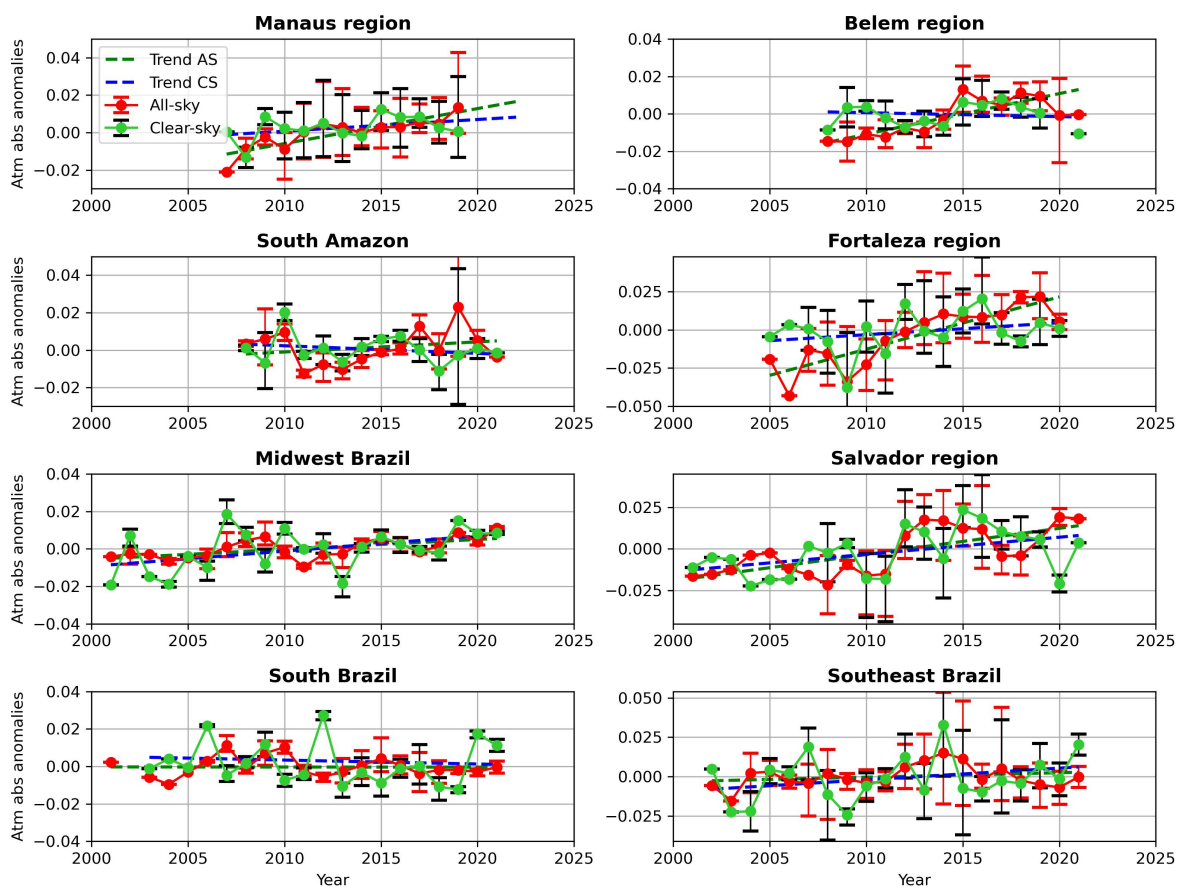
441 In Figure 5 (a) we see a strong negative AOD trend in the Southern Amazon in the period, and  
 442 slightly negative to near-zero trends in the rest of the country. Trends are statistically significant in the  
 443 Southern Amazon and in the inner area of the country down to approximately 15 degrees south (shaded  
 444 areas), while they lose significance towards the coast. The process that dominates the AOD trends in  
 445 the Southern Amazon (and in the whole country) is the reduction of biomass burning in the Amazon  
 446 region. The Southern part of the Amazon region is the area that suffers most from the biomass burning  
 447 (Artaxo et al., 2006), especially in the dry season during the southern hemisphere winter. A reduction  
 448 in forest fires at the beginning of the 21st century has been reported (Silva Junior et al., 2021), and its  
 449 effect is clear in the AOD trends. This result is consistent with the observed clear-sky SSR brightening  
 450 in the Southern Amazon, but challenges the negative clear-sky SSR trends observed in most of the  
 451 country. This suggests that changes in AOD were not primarily responsible for the clear-sky SSR trends  
 452 in the whole of Brazil, with the exception of the Southern Amazon region.

453 The water vapour trend map (Figure 5 (b)) shows remarkably negative trends in the central  
 454 Amazon, in a region around the east coast of Brazil and in the southernmost part of the country.  
 455 Remarkably positive trends are present from the middle Western Brazil (south of the Amazon region)

456 stretching to Southeastern Brazil, and in the northeast and north coastal regions of the country. The  
 457 spatial distribution of the decadal variability of water vapour does not generally comply with the  
 458 observed clear-sky SSR trends. We used these trends to estimate the change in atmospheric clear-sky  
 459 absorption due to solely water vapour, using the empirical model presented by Hakuba et al. (2016).  
 460 Based on these estimations, even in a region with strong water vapour trend such as Midwest Brazil,  
 461 these changes would be responsible for an increase in atmospheric clear-sky absorption (and  
 462 consequently decrease in SSR) of approximately  $0.4 \text{ W/m}^2$  per decade. This is almost one order of  
 463 magnitude smaller than the clear-sky SSR trends in the region ( $-1.8$  and  $-2.5 \text{ W/m}^2$  per decade, for  
 464 clear-sky conditions based on Correa et al. (2022) and Synop cloud cover, respectively). This suggests  
 465 that the water vapour contribution to the observed clear-sky SSR trends, when existed, was only minor.

### 466 3.3 Atmospheric absorption and Anthropogenic emissions

467 To better understand the reasons behind the observed clear-sky SSR trends and the overall  
 468 processes responsible for the all-sky SSR trends, we analyzed the changes in fractional atmospheric  
 469 absorption under all-sky and clear-sky conditions. This is a relevant aspect to be assessed, because  
 470 changes in atmospheric shortwave absorption can be an important driver of SSR trends (Schwarz et al.,  
 471 2020). Figure 6 shows these time series for the composites considered in this study both under all-sky  
 472 and clear-sky conditions.

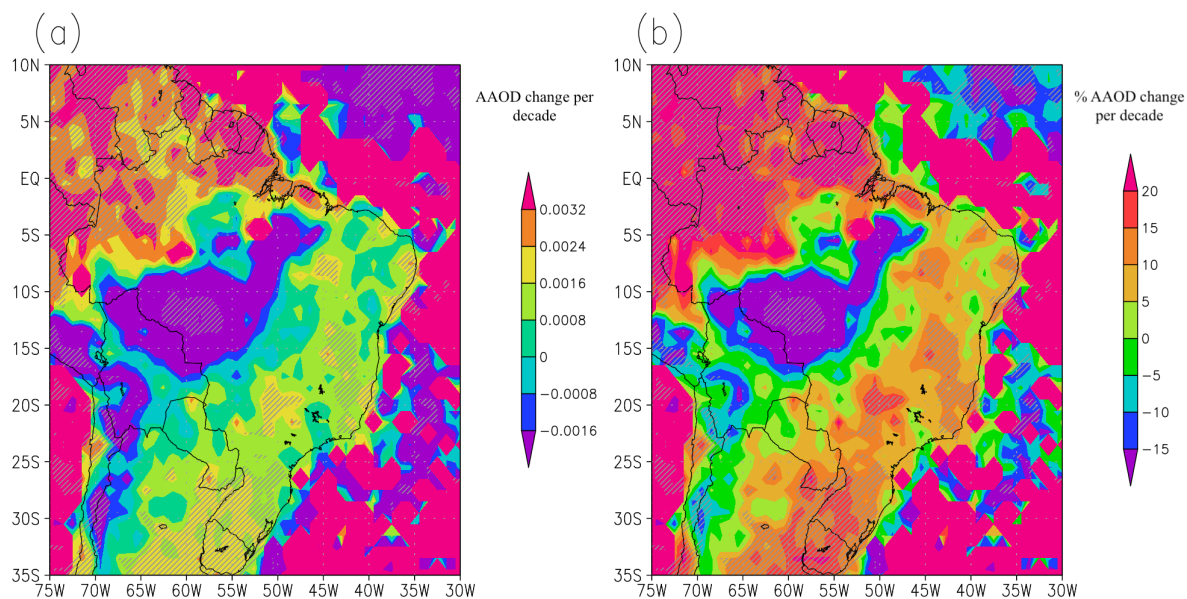


474 **Figure 6: Time series of all-sky (red) and clear-sky (green) fractional atmospheric column absorption**  
475 **annual anomalies for the eight composites used in this study.**

476 The fractional atmospheric absorption under all-sky conditions increased in most of the  
477 composites in the first two decades of the 21st century. Five composites showed statistically significant  
478 positive trends in  $F_{\text{abs}}$ , they are: Manaus, Belem, Fortaleza, Salvador and Middle West. The other  
479 composites also showed positive trends, but they were statistically insignificant. Under clear-sky  
480 conditions, the trends are obviously smaller, as the cloud induced multiple scattering does not play a  
481 role in enhancing column absorption. Only in the Salvador and Middle West composites statistically  
482 significant positive trends were observed in the atmospheric absorption under clear-sky conditions. All  
483 the other composites show statistically insignificant trends with the same sign as their all-sky  
484 counterparts, with the exception of the South Amazon, which shows statistically insignificant negative  
485 trends under clear-sky, contrasting to a statistically insignificant positive trend under all-sky conditions.

486 These results reveal two important aspects of the SSR variability in Brazil. First, in seven out  
487 of the eight composites the changes in clear-sky absorption comply with the clear-sky SSR trends. That  
488 is, increasing (decreasing) clear-sky atmospheric absorption was always linked to a decrease (increase)  
489 in clear-sky SSR. Secondly, the presence of clouds greatly increased atmospheric absorption (not  
490 shown) but also its trends. This has most likely happened because of the intensification of multiple  
491 scattering occurring under partially cloudy skies, resulting in a magnification of the trends seen in clear-  
492 sky conditions. This is reinforced by the fact that the strongest all-sky atmospheric absorption trends  
493 were found in the four cloudiest composites (Manaus, Belem, Fortaleza and Salvador), which happen  
494 to be the four composites with statistically significant negative all-sky SSR trends (dimming). Even  
495 though these results are consistent with each other, they also suggest that AOD only showed strong  
496 trends in the South Amazon region, and that water vapour only contributed as a minor part to the  
497 observed changes in atmospheric absorption (see discussion above). Thus, this raises the question of  
498 what could be the main responsible for the changes in atmospheric absorption in Brazil. To try to answer  
499 this question, we analyzed the decadal trend in aerosol absorption optical depth (AAOD) at 500 nm  
500 from OMI. The trend map is displayed in Figure 7.

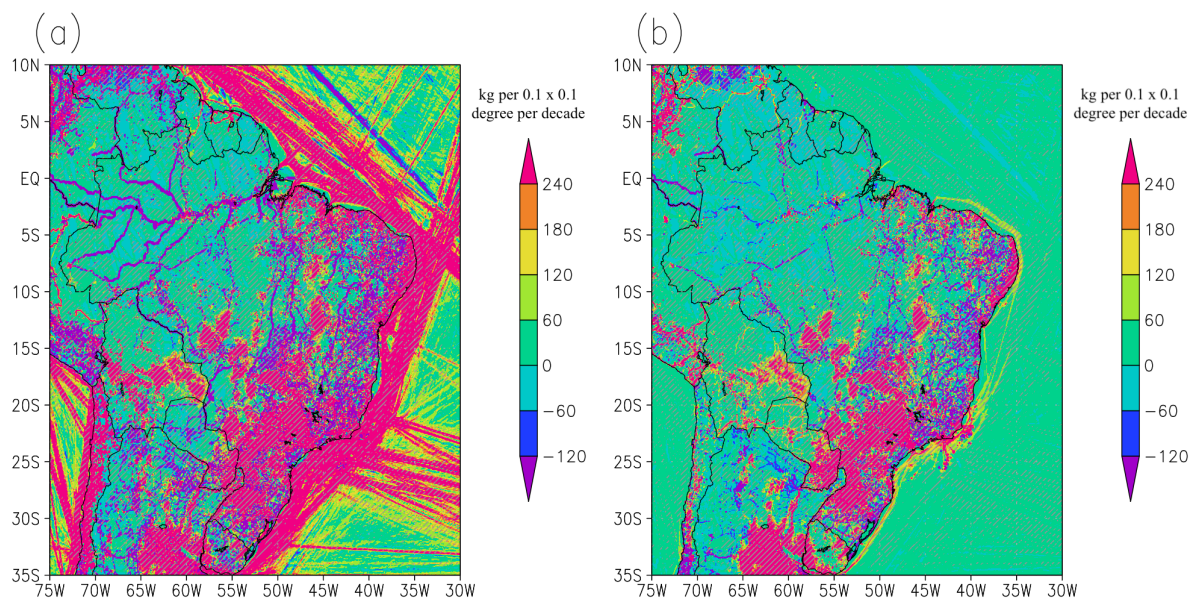




501  
 502 **Figure 7: (a) Absolute and (b) relative (%) decadal trends in Absorption Aerosol Optical Depth (AAOD)**  
 503 **in the 2005-2022 period from OMI. Shaded areas indicate statistical significance (at the 95% confidence**  
 504 **level).**

505         The map shows a clear distinction between the region under strong influence of the forest fires  
 506 in the Amazon (South Amazon) and the rest of Brazil. In the South Amazon, the data shows a decrease  
 507 in AAOD in the 2005-2022 period, while in the rest of the country an increase in absorption AAOD at  
 508 500 nm is observed. The spatial distribution of the trends suggests that the reduction in AAOD in the  
 509 South Amazon could be associated with the forest fires reduction also visible in the AOD trends. In the  
 510 whole rest of the country, positive trends in AAOD are observed. This reveals a significant change in  
 511 the optical properties of the aerosols present in Brazil in the first two decades of the 21st century, with  
 512 a trend towards more absorbing aerosols (at 500 nm) in most of the country. The AOD trend map  
 513 (Figure 5a) shows that in the same areas where AAOD increases, AOD remains nearly constant, with  
 514 trends close to zero. In order to better visualize potential reasons for an increase in AAOD at 500 nm  
 515 in most of Brazil, we also investigated trends in anthropogenic SO<sub>2</sub> and Black Carbon emissions in  
 516 Brazil. They are displayed in Figure 8.





517  
 518 **Figure 8: Decadal trends of annual mean (a) SO<sub>2</sub> and (b) Black Carbon anthropogenic emissions (in kg per**  
 519 **0.1x0.1 degree grid per decade) for the 2001-2018 period from EDGAR. Shaded areas indicate statistical**  
 520 **significance (at the 95% confidence level).**

521 They show a general increase in anthropogenic emissions in most of Brazil, especially in highly  
 522 populated areas. The only areas not showing increase in anthropogenic emissions are in the Amazon  
 523 rainforest. This might be counterintuitive when comparing the emissions trends (figure 8) with AOD  
 524 trends (figure 5a), as the strongest AOD trend is observed in the south of the Amazon region. However,  
 525 EDGAR emission estimates do not consider large scale biomass burning, land use change and forestry  
 526 (Crippa et al., 2018). As discussed in section 3.2, the AOD negative trend is mostly associated with  
 527 reductions in biomass burning in the first two decades of the 21st century in the Amazon. Therefore,  
 528 the biggest cause of the AOD trend (Figure 5a) is not considered in the emission data used in Figure 8.

529 Even though, according to figure 8, anthropogenic emissions did not increase significantly in  
 530 the Amazon region, emissions still increased around the biggest cities in the region, like Manaus and  
 531 Belem. This is of special relevance for this study, since seven of the eight composites are centered  
 532 around cities with over a million inhabitants, where the large and usually increasing population (Lobo  
 533 and Cunha, 2019) plays an important role to the atmospheric composition. The only composite that  
 534 does not follow this rule is the South Amazon composite, where the biggest city is Porto Velho, which  
 535 in 2020 had a population of less than 500'000 people (IBGE 2022). As anthropogenically emitted  
 536 aerosols tend to account for a larger fraction of solar radiation absorption than natural aerosols (Wang

537 et al., 2009), this increase in anthropogenic emissions (especially of black carbon) complies with the  
538 increasing AAOD in most of Brazil. Even though sulphate aerosols absorb much less shortwave  
539 radiation than black carbon, the increasing presence of scattering aerosols can also have a similar effect  
540 to the presence of broken clouds for atmospheric absorption (as discussed for the composites in North  
541 and Northeast Brazil): they increase multiple scattering, increasing the optical path of the photons,  
542 which increases the chances for absorption by the atmosphere. Therefore, the increasing anthropogenic  
543 emissions complies with the observed increase in atmospheric absorption in most of Brazil in the period  
544 of study. Similar results indicating a stronger impact of the changes in optical properties of the aerosols  
545 than the changes in aerosol optical depth on the observed SSR trends were also found for Japan in the  
546 1990s by Kudo et al. (2012).

## 547 **4. Discussion**

### 548 **4.1 Physical consistency of the results**

549 The results of this study point to a relevant impact of changes in atmospheric absorption in at  
550 least half of the regions analyzed. However, this is based on the fractional atmospheric absorption data,  
551 which is derived (as described in section 2.4) by combining in situ SSR (point) measurements with  
552 gridded data of surface albedo and outgoing shortwave radiation at TOA, at 0.25 and 1.0 degree spatial  
553 resolution, respectively. So the first question to be addressed is whether these results can be trusted  
554 even with the use of different spatial resolutions. Schwarz et al. (2018) investigated the spatial  
555 representativeness of SSR measurements in many stations around the world, including four stations in  
556 Brazil: Florianopolis, São Martinho da Serra (both in South Brazil), Brasilia (in Middle West) and  
557 Petrolina (~ 450 km away from Salvador). The authors found a good representativity of SSR for the 1-  
558 degree surroundings at most stations around the world at the monthly time scales, with estimated  
559 decorrelation lengths (the distance over which a point measurement is representative) always higher  
560 than 3 degrees in all of the four Brazilian locations. Madhavan et al. (2017) investigated spatial  
561 representativeness of SSR measurements at shorter time scales, and found that point measurements  
562 were representative to a 10 x 10 km area in time scales up to around one hour (from 26 minutes at  
563 overcast conditions to 70 minutes at broken clouds conditions). The authors demonstrated that the  
564 decorrelation lengths increase linearly (on a log-log scale) with decreasing frequency (longer time  
565 averaging). Following the results of the study by Madhavan et al. (2017), this would lead to  
566 decorrelation lengths around the order of 100 km (~1 degree) at the daily (24-hour) time scales.  
567 Therefore, based on the interpretation of these results, we can expect a satisfactory consistency in the  
568 results from combining point measurements at the surface with 1-degree measurements at the TOA at  
569 daily time scales, as done in this study. An in-depth analysis to estimate the decorrelation lengths at  
570 daily time scales of each station goes beyond the scope of the study.

571 The performance of the gridded products used used in this study are discussed in their  
572 respective documentations, referenced in section 2. Spectral surface albedo is reported as a main source  
573 of uncertainty in the satellite based products, especially OMI AAOD, however, this tends to be a major  
574 problem over the ocean. Sub-grid cloud contamination tends to also represent a problem for the retrieval  
575 of satellite based products. But this is reported to lead to an over/under estimation of the average AAOD,  
576 but should not affect the representation of its long-term variability. No issues with the long-term  
577 variability of the reanalysis products were reported.

578 Regarding atmospheric absorption, previous studies (e.g. Li et al., 1995; Byrne et al., 1996)  
579 have shown an enhancement in atmospheric absorption under cloudy conditions. According to previous  
580 literature, such an enhancement would not be caused by cloud absorption, but by cloud scattering, which  
581 increases the optical path of a photon in the atmosphere, consequently increasing the chances of this  
582 photon to be absorbed by other components of the atmosphere, such as water vapour and aerosols. Even  
583 though the existence of this mechanism is clear, the quantitative influence this could have on the energy  
584 budget at any location would also depend on the characteristics of cloud occurrence (e.g. the frequency  
585 of cloud free, overcast and partially cloudy conditions). As much as cloud free conditions are not  
586 optimal for atmospheric absorption, completely overcast conditions are not either. Under fully cloudy  
587 conditions, the backscattering of incoming shortwave radiation is high, usually not increasing the  
588 optical path of the photons and not allowing them to reach lower levels of the atmosphere, where water  
589 vapour and aerosol concentrations are higher. Thus, the high occurrence of partially cloudy conditions  
590 would increase the cloud effects on atmospheric absorption, via the increase in the optical path of the  
591 photons. Such conditions are found in Belem, Manaus, Fortaleza and Salvador, due to the importance  
592 of local convection for cloud formation in such hot and humid locations. The differences in the  
593 fractional atmospheric absorption trends between clear-sky and all-sky conditions at these locations  
594 reinforces this: trends under all-sky conditions are one order of magnitude larger than their clear-sky  
595 counterparts. This is not observed at all the other locations, which have a higher dependence on  
596 mesoscale and synoptic scale phenomena for cloud formation than the previously mentioned locations.  
597 In fact, a difference in the precipitation regimes between the region where all the four above-mentioned  
598 composites are located and the rest of Brazil has already been pointed out by Reboita et al. (2010) and  
599 by Ferreira and Reboita (2022).

600 Chtirkova et al. (2023) investigated the potential effect of internal variability on the SSR trends,  
601 and the relevance especially of Atlantic oceanic modes like the Atlantic Meridional Mode (AMM) or  
602 the Atlantic Multidecadal Oscillation (AMO) to affect SSR trends by changing cloudiness in Brazil.  
603 The AMM and AMO went to lower values during the period of study (2001-2022), which should lead  
604 to decreasing SSR in Northeastern Brazil. This is consistent with the negative SSR trends in the region.  
605 But it is important to note that this reduction in the oceanic modes values did not represent a major  
606 phase transitions of these modes. A major increase in AMO occurred in the 1990s, and the cloud cover  
607 trends (from ERA5) for the 1990-2006 period show a strong decrease in cloud cover in most of Brazil,

608 especially the south and western part of the country. No SSR data was available for further investigation  
 609 in this study, but the importance of internal variability for SSR trends should not be neglected in future  
 610 studies

611 The trends in SSR and supporting information in the eight composites made it possible to  
 612 separate the discussion of the causes for the SSR trends into three groups. The composites in each group  
 613 and their common characteristics are listed on table 2.

Composites	Common characteristics
Manaus, Belem, Fortaleza and Salvador	Strong all-sky dimming
	Distinguished clear-sky dimming with lower magnitude than the all-sky
	Positive cloud cover trends
	Positive trends in all-sky atmospheric absorption
	Positive trends in clear-sky atmospheric absorption, but one order of magnitude smaller than their all-sky counterparts (this item does not apply to Salvador)
Southeast Brazil and Midwest Brazil	Strong negative cloud cover trends
	Negative clear-sky SSR trends
	Negative and statistically insignificant SSR trends
South Amazon and South Brazil	Statistically insignificant all-sky brightening
	Statistically insignificant clear-sky brightening

614

615 **Table 2: Groups of composites with and their common characteristics as indicated by the results**  
 616 **presented in this study.**

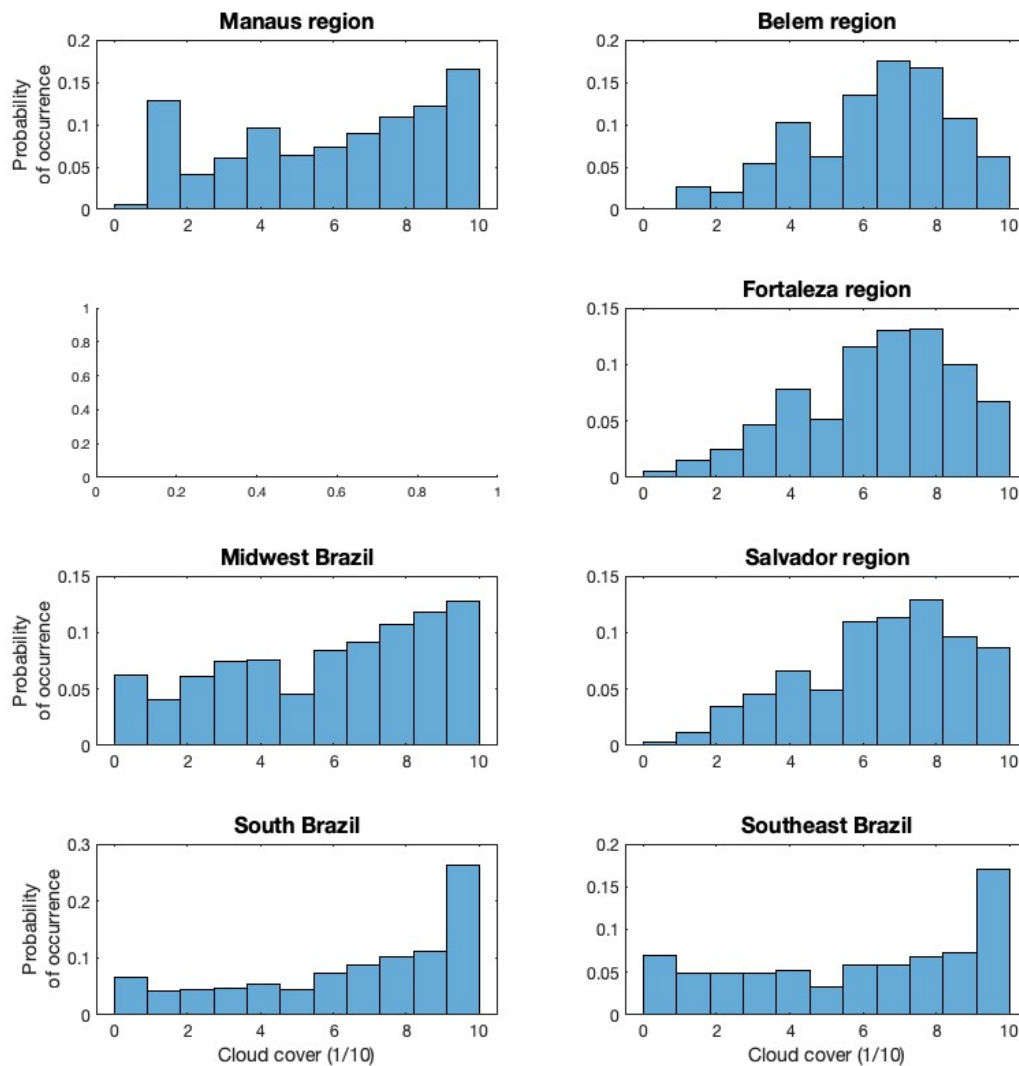
617 Based on this, we separated the discussion on the causes for SSR trends in three sections, each  
 618 discussing one of the three groups.

#### 619 **4.2 Dimming in North and Northeastern Brazil**

620 In this section, we discuss the dimming observed in the Manaus, Belem, Fortaleza and Salvador  
 621 composites, located in North and Northeastern Brazil. All of the composites showed statistically  
 622 significant all-sky dimming in the period, associated with a clear-sky dimming which was statistically  
 623 significant in all composites, except Manaus. The difference in the magnitude of the all-sky SSR trends  
 624 (from  $-6.3 \text{ W/m}^2$  per decade in Salvador to  $-18.8 \text{ W/m}^2$  per decade in Fortaleza) to the clear-sky SSR  
 625 trends (from  $-2.0 \text{ W/m}^2$  per decade in Manaus to  $-4.8 \text{ W/m}^2$  per decade in Belem) in the four composites  
 626 suggests that the clear-sky processes alone are unlikely to be strong enough to explain the SSR trends

627 in these locations. However, the fact that the clear-sky trends show the same sign as the all-sky trends,  
628 with (in most cases) statistical significance, indicates that processes occurring under clear-skies did  
629 contribute significantly to the overall trends. The contrast between all-sky and clear-sky also indicates  
630 a potential contribution of changes in cloud cover to the trends. In fact, we identified positive cloud  
631 cover trends, consistent with the observed reduction in SSR, but the magnitude of the trends (from 0.8  
632 % per decade in Fortaleza to 1.9 % per decade in Salvador) and the resulting impact of these cloud  
633 cover trends on the SSR trends, estimated by the CCRE (see Table 1), is small when compared to the  
634 SSR trends. Thus, our results (summarised in the table 1) suggest contributions from both clear-sky  
635 processes and cloud cover to the SSR trends, but none of them show a remarkable dominance compared  
636 to the other.

637 Further analysis of the atmospheric absorption showed strong positive (and statistically  
638 significant) trends in atmospheric absorption in all four composites. Schwarz et al. (2020) have shown  
639 that changes in atmospheric shortwave absorption can be an important driver of dimming and  
640 brightening. We also found that the atmospheric absorption trends were greatly enhanced by the  
641 presence of clouds. This happens because the scattering by clouds increases the optical path of the  
642 photons. This effect occurs primarily under broken clouds conditions, when three-dimensional multiple  
643 scattering magnifies this effect. Our findings comply with the results presented by Byrne et al. (1996)  
644 and references therein, which highlight the enhancement of atmospheric absorption of solar radiation  
645 under broken clouds conditions. Results from Li et al. (1995) also suggested that this effect is stronger  
646 in tropical regions, and the authors discuss that this is associated primarily aerosol and water vapour  
647 absorption rather than cloud absorption. The characteristics of the distribution of cloudiness in the four  
648 composites, displayed in Figure 9, might also play a role in this process. Stations from these composites  
649 tend to have frequent occurrences of partially cloudy conditions. In the Belem, Fortaleza and Salvador  
650 composites the daily cloud cover is between 25% and 80% in around two thirds of the days. For the  
651 Manaus and Midwest Brazil composites this range of cloud cover occurred in around half of the days  
652 and for South and Southeast Brazil composites this value is around one third. Thus, at the daily scale  
653 we see a dominance of partially cloudy occurrences at three out of the four composites discussed in this  
654 section. Even though the same distinguishable characteristic was not found for the Manaus composite  
655 at the daily scale, based on the regionalization of precipitation regimes by Reboita et al. (2010), we  
656 would expect the same finding at a more refined time scale also for the Manaus composite. That would  
657 be the expectation because of the higher relevance of local convection at hot and humid locations  
658 (convective clouds cause more broken cloud fields than large scale synoptic clouds) at the four  
659 composites discussed in this section, in comparison to the other composites, where mesoscale and  
660 synoptic meteorological systems tend to play a more important role for cloud formation. This higher  
661 occurrence of broken clouds in the regions of the four composites discussed in this section then tends  
662 to play an important role for the enhancement of atmospheric absorption.



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665 **Figure 9: Distribution of daily Synop cloud cover occurrences in seven out of the eight composites used in**  
 666 **this study. Not enough data was available to derive a distribution for the South Amazon composite.**

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A simple multiplication between the incoming TOA radiation at each composite and the trends in fractional all-sky atmospheric absorption (shown in Table 1) reveals an estimated increase in all-sky atmospheric absorption from approximately  $6 \pm 3 \text{ W/m}^2$  per decade in Belem up to  $14 \pm 5 \text{ W/m}^2$  per decade in Fortaleza. If we assume that such an increase in atmospheric absorption is directly reflected in a reduction in SSR, we find that the effect of changes in atmospheric absorption under all-sky conditions have a higher effect than the estimated clear-sky SSR trends (see table 1) and the estimated effects of changes in clouds cover (see CCRE in table 1), and are more consistent with the magnitude of the observed all-sky SSR trends (presented in table 1). Thus, these results suggest that the increase in atmospheric absorption was the strongest contributor for the negative SSR trends observed in these four composites in north and northeast Brazil, with contributions also from changes in cloud cover. The difference in the all-sky and clear-sky absorption trends at these four composites indicates that clouds played an important role in the increasing in absorption, most likely by enhancing the optical path of

679 photons via multiple scattering under partially cloudy conditions. The results also suggest that these  
680 changes in atmospheric absorption were greatly influenced by the changes in the optical properties of  
681 the aerosols present in these regions. Our results showed the occurrence of increasing anthropogenic  
682 emissions of SO<sub>2</sub> and black carbon, which did not seem to significantly change the AOD (possibly  
683 because of its competing effects with the reduction of biomass burning emissions in South Amazon),  
684 but increased the AAOD. This is most likely the cause for the increase in atmospheric absorption at the  
685 four composites. All of this points to a relevant influence of anthropogenic factors to the SSR trends in  
686 the first two decades of the 21st century in the regions around Manaus, Belem, Fortaleza and Salvador.  
687 Remembering that these are all big cities with over a million inhabitants each, therefore this result could  
688 be biased towards big population centers.

### 689 **4.3 Midwest and Southeast Brazil**

690 In this section we discuss the causes of the decadal SSR trends in the Middle West and  
691 Southeast Brazil composites. Both all-sky SSR composites show near-zero trends, with  $-0.4 \pm 2.7$  W/m<sup>2</sup>  
692 per decade in the Middle West and  $-0.6 \pm 5.4$  W/m<sup>2</sup> per decade in Southeast Brazil in the first two  
693 decades of the 21st century. Both composites show clear-sky SSR dimming (statistically significant in  
694 the Middle West and statistically insignificant in the Southeast) and statistically significant decrease in  
695 cloud cover in the period. An increase in atmospheric absorption was also observed at these locations,  
696 but the trends were substantially smaller than the trends observed in the four composites discussed in  
697 the previous section. These results already suggest different physical processes playing a role in the  
698 causes of SSR decadal trends in these regions.

699 The trends in fractional clear-sky atmospheric absorption in the two composites are similar to  
700 each other ( $0.0051 \pm 0.005$  per decade in the Middle West and  $0.0059 \pm 0.007$  per decade in the  
701 Southeast) and are larger than the trends in three out of the four composites discussed in the previous  
702 section. The clear-sky absorption trends are also larger than the all-sky absorption trends in the Middle  
703 West and Southeast. This indicates a bigger relative relevance of the cloud-free processes for the SSR  
704 trends in these two regions compared to the four locations previously discussed. This is reinforced by  
705 the clear-sky SSR dimming at the two locations, and is also most likely associated with increasing  
706 anthropogenic emissions, which lead to more absorptive aerosols, without significant change in AOD.

707 A comparison between the results of these two composites with the four composites in North  
708 and Northeast Brazil supports the discussion regarding the impacts of broken clouds to the solar  
709 atmospheric absorption and the distribution of cloud cover occurrences, presented in the previous  
710 section. As discussed by Reboita et al. (2010) and by Ferreira and Reboita (2022), in the region from  
711 Middle West to Southeastern Brazil a stronger influence of large scale synoptic meteorological systems  
712 like cold fronts, South Atlantic Convergence Zone (SACZ) and the South American Low Level Jet  
713 (SALLJ) contrasts with Northern and Northeastern Brazil, where local convection and circulation play  
714 a more important role. This leads to different precipitation and cloudiness regimes between the

715 composites discussed in this section and in previous section. These regimes magnify the effects of  
716 atmospheric absorption in the North and Northeastern Brazil, again fitting to the results by Li et al.  
717 (1995), while not doing so in the rest of the country.

718 The results of these two composites also show a significant positive effect of changes in cloud  
719 cover on the SSR trends. Strong significant negative trends in cloud cover were observed at both  
720 regions. As a result of the competing effects between cloud-free processes and changes in cloud cover,  
721 the resulting SSR trends in the first two decades of the 21st century were negative, but near-zero, for  
722 both composites. This shows opposing effects of anthropogenic (changes in aerosols) and natural  
723 (changes in cloud cover) changes canceling out.

#### 724 **4.4 South Amazon and South Brazil**

725 In this section we discuss the causes for the SSR decadal trends in the South Amazon and South  
726 Brazil. In both regions statistically insignificant brightening was observed in the all-sky SSR trends.  
727 Clear-sky SSR trends also showed brightening (statistically insignificant) in both regions. Cloud cover  
728 trends in South Brazil were rather small ( $-0.4$  [ $-1.4$ ;  $0.6$ ] % per decade), while cloud data was not  
729 available for South Amazon.

730 For the South Amazon, the most relevant aspect to be discussed is the strong negative trend in  
731 AOD observed in the study period, associated with the documented reduction in deforestation and  
732 biomass burning in the Amazon (Silva Junior et al., 2021). Amazon biomass burning aerosols play an  
733 important role in the atmospheric transmissivity in the region, but their emission, and consequently their  
734 effects, are highly seasonally dependent, as shown by Schwarz et al. (2019). For this reason, even  
735 though the annual AOD decadal trends show very strong negative values, the strong effects on SSR are  
736 present mostly in the dry season (southern hemisphere winter), and are smoothed out with annual means  
737 and decadal trends calculations. The seasonal clear-sky SSR trends in this composite are positive  
738 (statistically insignificant at the 95% confidence level) in winter and spring ( $5.0 \pm 5.6$  and  $1.1 \pm 3.9$   
739  $\text{W/m}^2$  per decade, respectively) and negative (statistically insignificant at the 95% confidence level) in  
740 summer and fall ( $-2.6 \pm 2.7$  and  $-1.6 \pm 3.3$   $\text{W/m}^2$  per decade, respectively), reinforcing this hypothesis.  
741 This smoothing of the AOD effects in the annual means and decadal trends is most likely the reason  
742 why, despite the strong negative AOD trends in the region, the all-sky and clear-sky SSR trends show  
743 positive trends with an absolute magnitude remarkably smaller than the trends observed in north and  
744 northeastern Brazil. This counterintuitive result (strong negative AOD decadal trend not resulting in  
745 strong brightening neither in all-sky nor in clear-sky SSR) reveals the importance of taking seasonality  
746 into account when investigating the response of SSR to changes in AOD.

747 In South Brazil, the SSR decadal trends are weakly positive, not of statistical significance, both  
748 under all-sky and clear-sky conditions. This suggests the lack of a strong driver for the SSR trends in  
749 the period analyzed. Cloud cover shows a small negative trend (statistically insignificant). Near-zero  
750 trends are also found in AOD and in atmospheric absorption. The map of AAOD at 500 nm shows small



751 positive trends in the period, but water vapour shows small negative trends. It is important to note that  
752 due to the logarithmic response of atmospheric absorption to changes in water vapour (e.g. Hakuba et  
753 al., 2016), this is the region in Brazil with the expected strongest sensitivity to changes in water vapour.  
754 Combining all these results together denotes competing small effects from different sources, and this is  
755 most likely the reason for the resulting non significant trend observed. Another relevant aspect to be  
756 highlighted, is that the period of analysis did not show a strong transition in the signal from oceanic  
757 modes in the Atlantic. Chtirkova et al. (2023) pointed out the importance of the AMM and AMO  
758 oceanic modes for the SSR trends in South America. This could be relevant for all composites, but the  
759 lack of strong effects on SSR changes of the existing forcing elements in South Brazil in the post 2000  
760 period let us to hypothesize that in a transitional period of AMM and/or AMO, internal variability could  
761 dominate the SSR trends in this region, especially via changes in cloud cover. This hypothesis is  
762 reinforced by the cloud cover trends from ERA5 for the 1990-2006 period (Figure A1, in appendix),  
763 which show strong negative cloud cover trends in the region associated with the transitioning of the  
764 AMO from a negative to a positive phase. The expectation is that the cloud cover trends in this period  
765 dominated the SSR trends, causing brightening in the last decade of the 20st century in South Brazil.  
766 However, the lack of SSR data before 2000 did not allow us to verify this hypothesis.

## 767 5. Conclusions

768 In this study we presented and investigated the magnitudes of the SSR trends and their  
769 associated causes over the first two decades of the 21st century based on 34 stations in Brazil, divided  
770 into 8 composites of 3 to 5 stations each. These are: Manaus region, Belem region, South Amazon,  
771 Fortaleza region, Middle west, Salvador region, Southeast Brazil and South Brazil. The exact temporal  
772 coverage of the SSR time series was composite-dependent, covering 22 years (2001-2022) in the four  
773 southernmost composites (South, Southeast, Middle West and Salvador), and only 14 years (2008-  
774 2021) in the South Amazon composite, the shortest time spam of all composites in this study. The  
775 limited length of the periods should be kept in mind, as they are shorter than the long-term  
776 dimming/brightening studies performed in regions like Europe.

777 We used cloud cover data from in situ measurements, clear-sky SSR time series derived with  
778 two different methods (using Synop cloud cover and using the method by Correa et al., 2022),  
779 atmospheric absorption calculated combining in situ and satellite measurements, AOD from the CAMS  
780 reanalysis, AAOD from OMI satellite observations and anthropogenic emissions from EDGAR to  
781 investigate the causes of the SSR trends in the eight composites in their period of data availability. All  
782 in-situ data went through quality control procedures to attest their validity and documentation of gridded  
783 data was carefully considered to account for potential issues. Our results showed that a strong dimming  
784 occurred in the composites located in north and northeast Brazil (Manaus, Belem, Fortaleza and

785 Salvador) in the period of study, while the other four composites all showed statistically insignificant  
786 trends (positive in the South Amazon and South Brazil, and negative in the Southeast and Midwest).

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788 A detailed analysis on the data revealed significant contributions of both clear-sky SSR and  
789 cloud cover changes to the trends observed in the north and northeast Brazil, but with a dominance of  
790 the effects of increasing atmospheric absorption under all-sky conditions. This is believed to be  
791 associated with increased anthropogenic/urban emissions, which would also explain the clear-sky SSR  
792 dimming, and the characteristics of cloud occurrence in those regions. Previous studies (e.g. Li et al.,  
793 1995; Byrne et al., 1996) have discussed the increase in atmospheric absorption under broken cloud  
794 conditions due to the multiple scattering by clouds and absorption by water vapour and aerosols. The  
795 massive occurrence of partially cloudy conditions at these regions, in comparison with the other  
796 composites analysed in this study, make this mechanism much more relevant at the North and Northeast  
797 Brazil stations than in all of the others. The importance of changes in atmospheric shortwave absorption  
798 to dimming and brightening have also been highlighted by Schwarz et al. (2020). Even though in the  
799 present study we have been able to identify different factors significantly affecting SSR trends in these  
800 regions and their magnitude, future work would be important to more precisely quantify the  
801 contributions of each factors causing SSR changes and to project the contributions of these factors in  
802 the future.

803 In Southeast and Midwest Brazil, statistically insignificant negative SSR trends in the period  
804 indicated that no single strong forcing dominated dimming and brightening. Therefore, the small trends  
805 were most likely the result of competing effects of negative cloud cover trends (resulting in a positive  
806 forcing on all-sky SSR) and negative clear-sky SSR trends (resulting in a negative forcing on all-sky  
807 SSR), where the clear-sky trends are also most likely associated with changes in aerosol absorption  
808 (due to changes in anthropogenic/urban aerosols). In the South Amazon the signal of the strong aerosol  
809 reduction, resulting from the reduction in biomass burning in the Amazon at the beginning of the 21st  
810 century (Silva Junior et al., 2021), dominated the observed brightening. This AOD reduction covered a  
811 large area in central Brazil, but did not reach most of the other composites, and areas with the strongest  
812 negative AOD trends (stronger than  $-0.06$  per decade) were all located in the South of the Amazon.  
813 However, the resulting SSR trends (both all-sky and clear-sky) were not statistically significant. A  
814 potential reason for this might be the strong seasonality of the biomass burning in the Amazon (Schwarz  
815 et al., 2019), which means that the strong changes in AOD are affecting SSR only a few months per  
816 year, during winter and spring months (which might not be massively relevant since the stations in the  
817 composite are around 10-15 degrees south). Due to missing data we were not able to assess the extent  
818 of cloud cover contribution to this result. Finally in South Brazil, competing minor effects of cloud-free  
819 processes and cloud cover changes resulted in statistically insignificant brightening.

820 This study contributes to the understanding of the causes of SSR decadal trends in a world  
821 region with still limited observational data. Further research would, however, be largely relevant,

822 especially in the quantification of each of the factors causing SSR changes and in the estimation of these  
823 factors in the future.

#### 824 **Data availability**

825 The data from the IAG/USP station can be requested at  
826 [http://www.estacao.iag.usp.br/sol\\_dados.php](http://www.estacao.iag.usp.br/sol_dados.php) (last access: 21 Feb 2024). The data from  
827 INMET stations can be requested at <https://bdmep.inmet.gov.br/> (last access: 21 Feb 2024).  
828 The BSRN SSR data is available at the BSRN website (<https://bsrn.awi.de/>). The CERES  
829 products are available at the CERES website (<https://ceres.larc.nasa.gov/data/>). The ERA5  
830 reanalysis data used in this study is available under  
831 [https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-](https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means)  
832 [means](https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means) . The CAMS AOD reanalysis data is available under  
833 <https://www.ecmwf.int/en/research/climate-reanalysis/cams-reanalysis> . Data of  
834 anthropogenic emissions estimates is available at the EDGAR website  
835 ([https://edgar.jrc.ec.europa.eu/emissions\\_data\\_and\\_maps](https://edgar.jrc.ec.europa.eu/emissions_data_and_maps) , last access: 21 Feb 2024). The data  
836 from the OMI instrument used in this study is available at  
837 [https://disc.gsfc.nasa.gov/datasets/OMAERUVd\\_003/summary](https://disc.gsfc.nasa.gov/datasets/OMAERUVd_003/summary) (last access 21 Feb 2024). The  
838 satellite cloud fraction data from CLARA, used to apply the clear-sky method used in this  
839 study, can be found on the CM SAF website (<https://www.cmsaf.eu/>) and downloaded using  
840 the Web User Interface at <https://wui.cmsaf.eu/>

#### 841 **Author contributions**

842 LFC designed the study, organised the data and wrote the original manuscript. DF, BC and MW revised  
843 and edited the text. All authors contributed to the analysis and to the final paper.

#### 844 **Competing interests**

845 The authors declare that they have no conflict of interest.

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#### 853 **References**

854 Artaxo, P., Oliveira, P. H., Lara, L. L., Pauliquevis, T. M., Rizzo, L. V., Junior, C. P., ... &  
855 Correia, A. L. (2006). Efeitos climáticos de partículas de aerossóis biogênicos e

- 856 emitidos em queimadas na Amazônia. *Revista brasileira de meteorologia*, 21(3a),  
857 168-22.
- 858 Augustine, J. A., & Capotondi, A. (2022). Forcing for multidecadal surface solar radiation  
859 trends over Northern Hemisphere continents. *Journal of Geophysical Research:*  
860 *Atmospheres*, 127(16), e2021JD036342.
- 861 Byrne, R. N., Somerville, R. C. J., & Subařilar, B. (1996). Broken-cloud enhancement of  
862 solar radiation absorption. *Journal of Atmospheric Sciences*, 53(6), 878-886.
- 863 Chiacchio, M., & Wild, M. (2010). Influence of NAO and clouds on long-term seasonal  
864 variations of surface solar radiation in Europe. *Journal of Geophysical Research:*  
865 *Atmospheres*, 115(D10).
- 866 Chtirkova, B., Folini, D., Correa, L. F., & Wild, M. (2023). Internal variability of the climate  
867 system mirrored in decadal-scale trends of surface solar radiation. *Journal of*  
868 *Geophysical Research: Atmospheres*, e2023JD038573.
- 869 Correa, L. F., Folini, D., Chtirkova, B., & Wild, M. (2022). A Method for Clear-Sky  
870 Identification and Long-Term Trends Assessment Using Daily Surface Solar  
871 Radiation Records. *Earth and Space Science*, 9(8), e2021EA002197.
- 872 Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., Van Aardenne, J. A., ... &  
873 Janssens-Maenhout, G. (2018). Gridded emissions of air pollutants for the period  
874 1970–2012 within EDGAR v4. 3.2. *Earth Syst. Sci. Data*, 10(4), 1987-2013.
- 875 Da Silva, V. D. P. R., e Silva, R. A., Cavalcanti, E. P., Braga, C. C., de Azevedo, P. V.,  
876 Singh, V. P., & Pereira, E. R. R. (2010). Trends in solar radiation in NCEP/NCAR  
877 database and measurements in northeastern Brazil. *Solar Energy*, 84(10), 1852-  
878 1862.
- 879 de Jong, P., Barreto, T. B., Tanajura, C. A., Kouloukoui, D., Oliveira-Esquerre, K. P.,  
880 Kiperstok, A., & Torres, E. A. (2019). Estimating the impact of climate change on  
881 wind and solar energy in Brazil using a South American regional climate model.  
882 *Renewable energy*, 141, 390-401.
- 883 de Lima, F. J. L., Martins, F. R., Costa, R. S., Gonçalves, A. R., dos Santos, A. P. P., &  
884 Pereira, E. B. (2019). The seasonal variability and trends for the surface solar  
885 irradiation in northeastern region of Brazil. *Sustainable Energy Technologies and*  
886 *Assessments*, 35, 335-346.
- 887 Doelling, D. R., Loeb, N. G., Keyes, D. F., Nordeen, M. L., Morstad, D., Nguyen, C., ... &  
888 Sun, M. (2013). Geostationary enhanced temporal interpolation for CERES flux  
889 products. *Journal of Atmospheric and Oceanic Technology*, 30(6), 1072-1090.
- 890 Doelling, D. R., Sun, M., Nordeen, M. L., Haney, C. O., Keyes, D. F., & Mlynczak, P. E.  
891 (2016). Advances in geostationary-derived longwave fluxes for the CERES synoptic  
892 (SYN1deg) product. *Journal of Atmospheric and Oceanic Technology*, 33(3), 503-  
893 521.
- 894 Driemel, A., Augustine, J., Behrens, K., Colle, S., Cox, C., Cuevas-Agulló, E., ... & König-  
895 Langlo, G. (2018). Baseline Surface Radiation Network (BSRN): structure and data  
896 description (1992–2017). *Earth System Science Data*, 10(3), 1491-1501.
- 897 Dutton, E. G., Stone, R. S., Nelson, D. W., & Mendonca, B. G. (1991). Recent interannual  
898 variations in solar radiation, cloudiness, and surface temperature at the South Pole.  
899 *Journal of Climate*, 4(8), 848-858.

- 900 Feng, F., & Wang, K. (2019). Determining factors of monthly to decadal variability in  
901 surface solar radiation in China: Evidences from current reanalyses. *Journal of*  
902 *Geophysical Research: Atmospheres*, 124(16), 9161-9182.
- 903 Ferreira, G. W., & Reboita, M. S. (2022). A new look into the South America precipitation  
904 regimes: Observation and Forecast. *Atmosphere*, 13(6), 873.
- 905 Fisch, G., MARENGO, J. A., & NOBRE, C. A. (1998). Uma revisão geral sobre o clima da  
906 Amazônia. *Acta amazônica*, 28, 101-101.
- 907 Gilgen, H., Roesch, A., Wild, M., & Ohmura, A. (2009). Decadal changes in shortwave  
908 irradiance at the surface in the period from 1960 to 2000 estimated from Global  
909 Energy Balance Archive Data. *Journal of Geophysical research: atmospheres*,  
910 114(D10).
- 911 Gueymard, C. A., & Yang, D. (2020). Worldwide validation of CAMS and MERRA-2  
912 reanalysis aerosol optical depth products using 15 years of AERONET  
913 observations. *Atmospheric Environment*, 225, 117216.
- 914 Hakuba, M. Z., Folini, D., & Wild, M. (2016). On the zonal near-constancy of fractional solar  
915 absorption in the atmosphere. *Journal of Climate*, 29(9), 3423-3440.
- 916 Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., ... &  
917 Thépaut, J. N. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal*  
918 *Meteorological Society*, 146(730), 1999-2049.
- 919 IBGE. Censo Demográfico. Rio de Janeiro, Brazil: Fundação Instituto Brasileiro de  
920 Geografia e Estatística. 2022. Available at:  
921 <https://censo2022.ibge.gov.br/panorama/index.html> Last access: 01 Nov. 2023.  
922 <https://censo2022.ibge.gov.br/panorama/index.html>
- 923 Inness, A., Ades, M., Agustí-Panareda, A., Barré, J., Benedictow, A., Blechschmidt, A. M., ...  
924 & Suttie, M. (2019). The CAMS reanalysis of atmospheric composition.  
925 *Atmospheric Chemistry and Physics*, 19(6), 3515-3556.
- 926 Jiao, B., Su, Y., Li, Q., Manara, V., & Wild, M. (2023). An integrated and homogenized  
927 global surface solar radiation dataset and its reconstruction based on a convolutional  
928 neural network approach. *Earth System Science Data*.
- 929 Kambezidis, H. D., Kaskaoutis, D. G., Kharol, S. K., Moorthy, K. K., Satheesh, S. K.,  
930 Kalapureddy, M. C. R., ... & Wild, M. (2012). Multi-decadal variation of the net  
931 downward shortwave radiation over south Asia: The solar dimming effect.  
932 *Atmospheric Environment*, 50, 360-372.
- 933 Kazadzis, S., Founda, D., Psiloglou, B. E., Kambezidis, H., Mihalopoulos, N., Sanchez-  
934 Lorenzo, A., ... & Nabat, P. (2018). Long-term series and trends in surface solar  
935 radiation in Athens, Greece. *Atmospheric chemistry and physics*, 18(4), 2395-2411.
- 936 Kendall, M. G. (1975). Rank correlation methods. 2nd impression. *Charles Griffin and*  
937 *Company Ltd. London and High Wycombe*.
- 938 Kudo, R., Uchiyama, A., Ijima, O., Ohkawara, N., & Ohta, S. (2012). Aerosol impact on the  
939 brightening in Japan. *Journal of Geophysical Research: Atmospheres*, 117(D7).
- 940 Li, Z., Barker, H. W., & Moreau, L. (1995). The variable effect of clouds on atmospheric  
941 absorption of solar radiation. *Nature*, 376(6540), 486-490.
- 942 Liepert, B. G. (2002). Observed reductions of surface solar radiation at sites in the United  
943 States and worldwide from 1961 to 1990. *Geophysical research letters*, 29(10), 61-1.

- 944 Liley, J. B. (2009). New Zealand dimming and brightening. *Journal of Geophysical*  
945 *Research: Atmospheres*, 114(D10).
- 946 Lobo, C., & Cunha, J. M. P. D. (2019). Migração e mobilidade pendular nas áreas de  
947 influência de metrópoles brasileiras. *Mercator (Fortaleza)*, 18.
- 948 Long, C. N., & Dutton, E. G. (2002). BSRN Global Network Recommended QC Tests, V2.  
949 0, BSRN Technical Report.
- 950 Long, C. N., Dutton, E. G., Augustine, J. A., Wiscombe, W., Wild, M., McFarlane, S. A., &  
951 Flynn, C. J. (2009). Significant decadal brightening of downwelling shortwave in the  
952 continental United States. *Journal of Geophysical Research: Atmospheres*,  
953 114(D10).
- 954 Madhavan, B. L., Deneke, H., Witthuhn, J., & Macke, A. (2017). Multiresolution analysis of  
955 the spatiotemporal variability in global radiation observed by a dense network of 99  
956 pyranometers. *Atmospheric Chemistry and Physics*, 17(5), 3317-3338.
- 957 Manara, V., Brunetti, M., Celozzi, A., Maugeri, M., Sanchez-Lorenzo, A., & Wild, M.  
958 (2016). Detection of dimming/brightening in Italy from homogenized all-sky and  
959 clear-sky surface solar radiation records and underlying causes (1959–2013).  
960 *Atmospheric Chemistry and Physics*, 16(17), 11145-11161.
- 961 Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica: Journal of the*  
962 *econometric society*, 245-259.
- 963 Natsis, A., Bais, A., & Meleti, C. (2023). Trends from 30-Year Observations of Downward  
964 Solar Irradiance in Thessaloniki, Greece. *Applied Sciences*, 14(1), 252.
- 965 Nishizawa, S., & Yoden, S. (2005). Distribution functions of a spurious trend in a finite  
966 length data set with natural variability: Statistical considerations and a numerical  
967 experiment with a global circulation model. *Journal of Geophysical Research:*  
968 *Atmospheres*, 110(D12).
- 969 Norris, J. R., & Wild, M. (2007). Trends in aerosol radiative effects over Europe inferred  
970 from observed cloud cover, solar “dimming,” and solar “brightening”. *Journal of*  
971 *Geophysical Research: Atmospheres*, 112(D8).
- 972 Ohmura, A., & Lang, H. (1989). Secular variation of global radiation over Europe, in Current  
973 Problems in Atmospheric Radiation. *edited by J. Lenoble, & JF Geleyn*, 98, 301.
- 974 Ohmura, A., Dutton, E. G., Forgan, B., Fröhlich, C., Gilgen, H., Hegner, H., ... & Wild, M.  
975 (1998). Baseline Surface Radiation Network (BSRN/WCRP): New precision  
976 radiometry for climate research. *Bulletin of the American Meteorological Society*,  
977 79(10), 2115-2136.
- 978 Ohmura, A. (2009). Observed decadal variations in surface solar radiation and their causes.  
979 *Journal of Geophysical Research: Atmospheres*, 114(D10).
- 980 Pfeifroth, U., Sanchez-Lorenzo, A., Manara, V., Trentmann, J., & Hollmann, R. (2018).  
981 Trends and variability of surface solar radiation in Europe based on surface-and  
982 satellite-based data records. *Journal of Geophysical Research: Atmospheres*,  
983 123(3), 1735-1754.
- 984 Power, H. C. (2003). Trends in solar radiation over Germany and an assessment of the role of  
985 aerosols and sunshine duration. *Theoretical and Applied Climatology*, 76(1), 47-63.
- 986 Raichijk, C. (2012). Observed trends in sunshine duration over South America. *International*  
987 *Journal of Climatology*, 32(5), 669-680.

- 988 Reboita, M. S., Gan, M. A., Da Rocha, R. P., & Ambrizzi, T. (2010). Precipitation regimes in  
989 South America: a bibliography review. *Revista Brasileira de Meteorologia*, 25(2),  
990 185-204.
- 991 Rosário, N. E., Sauini, T., Pauliquevis, T., Barbosa, H. M., Yamasoe, M. A., & Barja, B.  
992 (2019). Aerosol optical depth retrievals in central Amazonia from a multi-filter  
993 rotating shadow-band radiometer calibrated on-site. *Atmospheric Measurement*  
994 *Techniques*, 12(2), 921-934.
- 995 Russak, V. (1990). Trends of solar radiation, cloudiness and atmospheric transparency during  
996 recent decades in Estonia. *Tellus B*, 42(2), 206-210.
- 997 Schwartz, R. D. (2005). Global dimming: Clear-sky atmospheric transmission from  
998 astronomical extinction measurements. *Journal of Geophysical Research:*  
999 *Atmospheres*, 110(D14).
- 1000 Schwarz, M., Folini, D., Hakuba, M. Z., & Wild, M. (2018). From point to area: Worldwide  
1001 assessment of the representativeness of monthly surface solar radiation records.  
1002 *Journal of Geophysical Research: Atmospheres*, 123(24), 13-857.
- 1003 Schwarz, M., Folini, D., Yang, S., & Wild, M. (2019). The annual cycle of fractional  
1004 atmospheric shortwave absorption in observations and models: spatial structure,  
1005 magnitude, and timing. *Journal of Climate*, 32(20), 6729-6748.
- 1006 Schwarz, M., Folini, D., Yang, S., Allan, R. P., & Wild, M. (2020). Changes in atmospheric  
1007 shortwave absorption as important driver of dimming and brightening. *Nature*  
1008 *Geoscience*, 13(2), 110-115.
- 1009 Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of*  
1010 *the American statistical association*, 63(324), 1379-1389.
- 1011 Silva Junior, C. H., Pessôa, A. C., Carvalho, N. S., Reis, J. B., Anderson, L. O., & Aragão, L.  
1012 E. (2021). The Brazilian Amazon deforestation rate in 2020 is the greatest of the  
1013 decade. *Nature ecology & evolution*, 5(2), 144-145.
- 1014 Stjern, C. W., Kristjánsson, J. E., & Hansen, A. W. (2009). Global dimming and global  
1015 brightening—An analysis of surface radiation and cloud cover data in northern  
1016 Europe. *International Journal of Climatology: A Journal of the Royal*  
1017 *Meteorological Society*, 29(5), 643-653.
- 1018 Torres, O., Tanskanen, A., Veihelmann, B., Ahn, C., Braak, R., Bhartia, P. K., ... & Levelt, P.  
1019 (2007). Aerosols and surface UV products from Ozone Monitoring Instrument  
1020 observations: An overview. *Journal of Geophysical Research: Atmospheres*,  
1021 112(D24).
- 1022 Vera, C., Baez, J., Douglas, M., Emmanuel, C. B., Marengo, J., Meitin, J., ... & Zipser, E.  
1023 (2006). The South American low-level jet experiment. *Bulletin of the American*  
1024 *Meteorological Society*, 87(1), 63-78.
- 1025 Wang, C., Jeong, G. R., & Mahowald, N. (2009). Particulate absorption of solar radiation:  
1026 anthropogenic aerosols vs. dust. *Atmospheric Chemistry and Physics*, 9(12), 3935-  
1027 3945.
- 1028 Wang, K., Ma, Q., Li, Z., & Wang, J. (2015). Decadal variability of surface incident solar  
1029 radiation over China: Observations, satellite retrievals, and reanalyses. *Journal of*  
1030 *Geophysical Research: Atmospheres*, 120(13), 6500-6514.

- 1031 Wang, X. L. (2008). Penalized maximal F test for detecting undocumented mean shift  
1032 without trend change. *Journal of Atmospheric and Oceanic Technology*, 25(3), 368-  
1033 384.
- 1034 Wild, M. (2009). Global dimming and brightening: A review. *Journal of Geophysical*  
1035 *Research: Atmospheres*, 114(D10).
- 1036 Wild, M., Wacker, S., Yang, S., & Sanchez-Lorenzo, A. (2021). Evidence for clear-sky  
1037 dimming and brightening in central Europe. *Geophysical Research Letters*, 48(6),  
1038 e2020GL092216.
- 1039 Xia, X., Chen, H., Li, Z., Wang, P., & Wang, J. (2007). Significant reduction of surface solar  
1040 irradiance induced by aerosols in a suburban region in northeastern China. *Journal of*  
1041 *Geophysical Research: Atmospheres*, 112(D22).
- 1042 Yamasoe, M. A., Rosário, N. M. É., Almeida, S. N. S. M., & Wild, M. (2021). Fifty-six years  
1043 of surface solar radiation and sunshine duration over São Paulo, Brazil: 1961–2016.  
1044 *Atmospheric Chemistry and Physics*, 21(9), 6593-6603.
- 1045 Yang, S., Wang, X. L., & Wild, M. (2018). Homogenization and trend analysis of the 1958–  
1046 2016 in situ surface solar radiation records in China. *Journal of Climate*, 31(11),  
1047 4529-4541.
- 1048 Yuan, M., Leirvik, T., & Wild, M. (2021). Global trends in downward surface solar radiation  
1049 from spatial interpolated ground observations during 1961–2019. *Journal of*  
1050 *Climate*, 34(23), 9501-9521.
- 1051 Zuluaga, C. F., Avila-Diaz, A., Justino, F. B., & Wilson, A. B. (2021). Climatology and  
1052 trends of downward shortwave radiation over Brazil. *Atmospheric Research*, 250,  
1053 105347.

## 1054 Appendix

Station	Composite	Coordinates	Does it include SYNOP cloud cover?	% of monthly data available
Manaus	Manaus region	3.10S 60.01W	yes	87
Coari	Manaus region	4.10S 63.14W	yes	74
Rio Urubu	Manaus region	2.63S 59.60W	no	75
Urucará	Manaus region	2.53S 57.75W	no	82
Belém	Belém region	1.41S 48.43W	yes	95
Castanhal	Belém region	1.30S 47.94W	no	71
Tucuruí	Belém region	3.82S 49.67W	yes	92
Salinópolis	Belém region	0.62S 47.35W	no	69
Alta Floresta	South Amazon	10.07S 56.17W	no	62
Ariquemes	South Amazon	9.94S 62.96W	no	73
Juína	South Amazon	11.37S 58.77W	no	78



Porto Velho	South Amazon	8.79S 63.84W	no	73
Sorriso	South Amazon	12.55S 55.72W	no	85
Fortaleza	Fortaleza region	3.81S 38.53W	yes	68
Areia	Fortaleza region	6.97S 35.71W	yes	85
Caicó	Fortaleza region	6.46S 37.08W	yes	68
Natal	Fortaleza region	5.83S 35.20W	yes	65
Brasília	Midwest	15.78S 47.92W	yes	84
Goiânia	Midwest	16.64S 49.22W	yes	94
Campo Grande	Midwest	20.44S 54.72W	yes	79
Salvador	Salvador region	13.00S 38.50W	yes	89
Cruz das Almas	Salvador region	12.67S 39.08W	yes	66
Feira de Santana	Salvador region	12.19S 38.96W	yes	64
Itirucu	Salvador region	13.52S 40.11W	yes	61
Curitiba	South	25.44S 49.23W	yes	72
Porto Alegre	South	30.05S 51.17W	yes	95
Santa Maria	South	29.72S 53.72W	yes	89
Florianópolis*	South	27.60S 48.52W	yes	
Campos do Jordão	Southeast	22.75S 45.60W	yes	69
Monte Verde	Southeast	22.86S 46.04W	no	84
Rio de Janeiro - Marambaia	Southeast	23.05S 43.59W	yes	78
Seropédica	Southeast	22.75S 43.68W	no	98
São Paulo*	Southeast	23.65S 46.62W	yes	99

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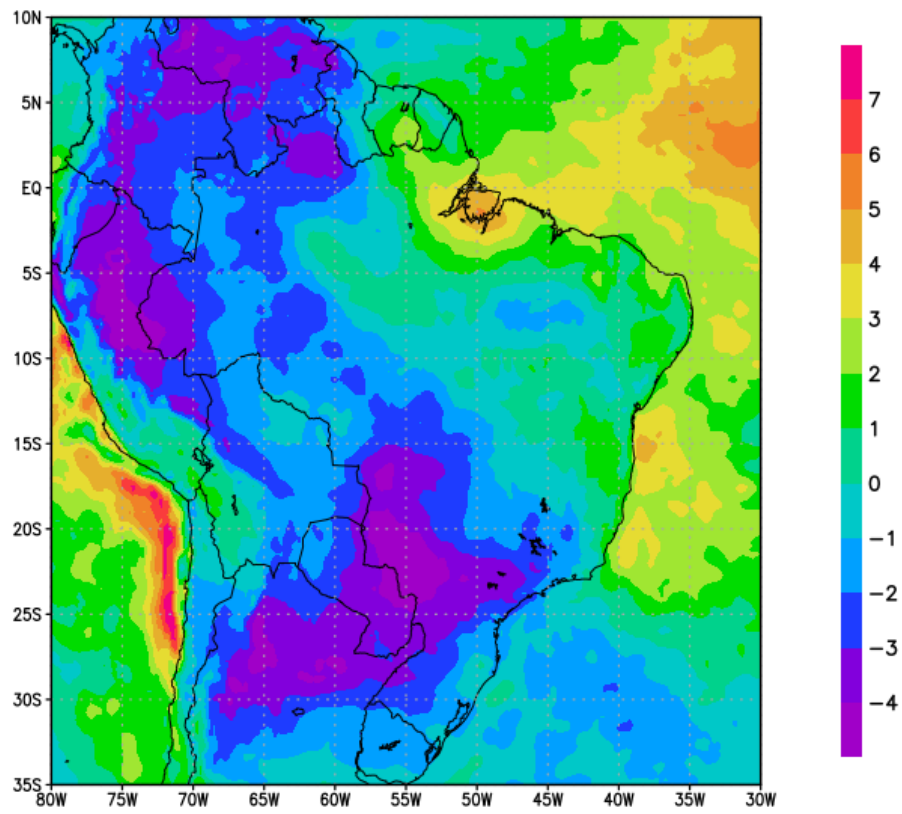
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**Table 3: Stations used in the study, the composites they were associated with, their coordinates, information whether Synop cloud cover data was available and the percentage of months with available data (out of all the months in the period used for the respective composite - see table 1). \*Stations not from the Brazilian National Institute of Meteorology. Florianópolis station from BSRN; São Paulo station from the Institute for Astronomy, Geophysics and Atmospheric Sciences at the University of São Paulo.**

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1064 **Figure A1 - Total cloud cover trends for the 1990-2006 period (in % per decade) from ERA5.**