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Journal Article

Author(s):
Philipona, Rolf; Marty, Christoph; Duerr, Bruno; Ohmura, Atsumu

Publication date:
2023-06-26

Permanent link:
https://doi.org/10.3929/ethz-b-000599336

Originally published in:
Meteorologische Zeitschrift 32(1), https://doi.org/10.1127/metz/2022/1148

Meteorol. Z. (Contrib. Atm. Sci.), Vol. **32**, No. 1, 5–14 (published online January 17, 2023)

Climatology

Rising solar and thermal greenhouse radiation drive rapid warming over continents

ROLF PHILIPONA[1*], CHRISTOPH MARTY[2], BRUNO DUERR[3] and ATSUMU OHMURA[4]

[1]Federal Office of Meteorology and Climatology MeteoSwiss (retired), Payerne, Switzerland
[2]WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland
[3]Sunergy GmbH, Degersheim, Switzerland
[4]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland

(Manuscript received April 28, 2022; in revised form September 26, 2022; accepted October 15, 2022)

Abstract

Rising anthropogenic greenhouse gases, such as CO_2, CH_4, N_2O and others, are known to absorb and emit terrestrial thermal radiation back to the Earth's surface, leading to radiative forcing and rising surface temperatures. Nonetheless, radiation measurements now show that the rapid increase in temperature over continents since the end of the last century, which is more than twice as large as the average global warming, is also related to a clearing of the sky over land surfaces, which leads to an increase in sunshine hours, and hence, increasing solar radiation absorbed at the Earth's surface. By contrasting rising temperatures with annual sunshine hours and solar and thermal radiation in Central Europe, the measurements show that thermal radiation steadily increases owing to the rising greenhouse effect. However, the rapidly increasing warming since the end of the last century has been reinforced by a strong increase in solar radiation at the surface, resulting from rising annual sunshine hours as a positive greenhouse warming feedback, which is larger than the increase in thermal greenhouse radiation, and hence, the strongest driver of the rapidly increasing warming over continents. The rapid temperature increase in Central Europe, of more than one degree over the last decade, is larger in lowlands than in the Alps.

Keywords: solar radiation, thermal greenhouse radiation, radiation measurements, rapidly increasing warming over continents

1 Introduction

Surface measurements show that the Earth's global average surface temperature has increased by approximately 1 °C since the mid of the nineteenth century (IPCC, 2021). The temperature increase over the planet is not uniform but is generally larger over land and particularly large over arctic regions (MANN et al., 2008). Significant trends in temperature and precipitation extremes have been observed in recent decades (FISCHER and KNUTTI, 2015), and eight of the ten warmest years since the beginning of meteorological measurements (PFISTER et al., 2019) have occurred during the last decade (ARGUEZ et al., 2020).

Global warming is caused by the enhanced absorption of terrestrial longwave radiation by anthropogenic greenhouse gases such as CO_2, CH_4, N_2O and others, which alters the energy balance of the Earth-atmosphere system and causes radiative forcing (FORSTER et al., 2007). Radiative forcing raises temperatures at the surface and in the troposphere, which leads to an increase in water vapor, the strongest greenhouse gas, thereby strengthening the greenhouse effect through water vapor feedback (LACIS et al., 2010).

Solar radiation is the main energy source of our planet and has been measured at the Earth's surface as direct and global radiation for more than a century (FRÖHLICH, 1991). Total solar irradiance (*TSI*) has been measured from space since 1979 (WILLSON, 1997; FRÖHLICH and LEAN, 2004) and composite time series are now available over four solar cycles (FOUKAL et al., 2006; KOPP and LEAN, 2011; FINSTERLE et al., 2021). The amount of solar energy that Earth receives has followed Sun's natural 11-year cycle, which shows a minor decrease since the beginning of satellite measurements (KOPP and SHAPIRO, 2021). Over the same period, global temperatures have increased markedly. Therefore, it is extremely unlikely that the Sun has caused the observed global warming trend over the past four decades (CODDINGTON et al., 2016).

Terrestrial longwave radiation has been reliably measured at the Earth's surface since the 1990s (PHILIPONA et al., 2001) and radiation networks have registered an increasing trend of longwave downward irradiance (OHMURA et al., 1998; PHILIPONA et al., 2004). Radiance spectra of outgoing shortwave and longwave radiation at the top of the atmosphere, measured by satellites since the late 1960s, allow for estimates of the radiation budget and investigations of the radiative forcing of climate in the Earth-atmosphere system (RASCHKE et al., 1973; RAMANATHAN et al., 1989; TRENBERTH et al., 2009).

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[*]Corresponding author: Rolf Philipona, Tschuggenstrasse 39, 7260 Davos Dorf, Switzerland, e-mail: rolf.philipona@gmail.com

DOI 10.1127/metz/2022/1148
Gebrüder Borntraeger Science Publishers, Stuttgart, www.borntraeger-cramer.com

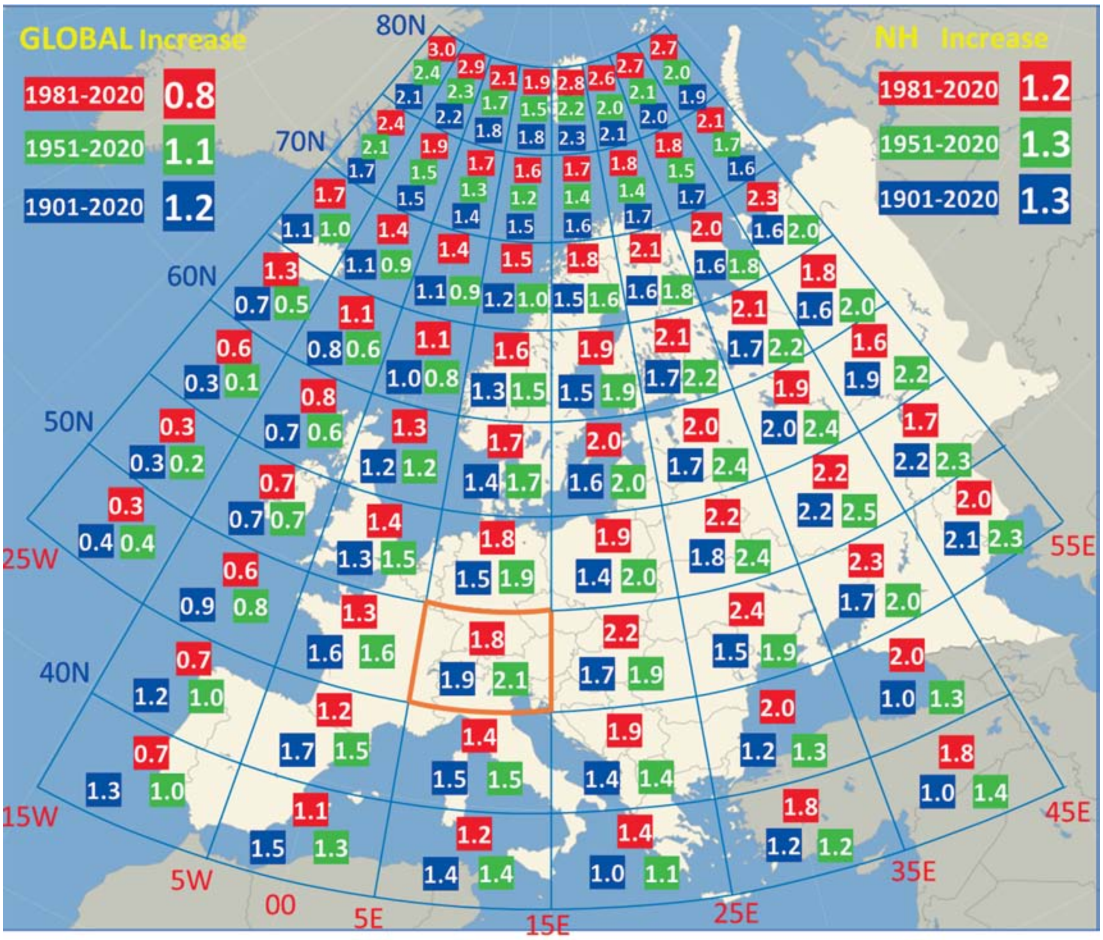

Figure 1: Global, NH and Europe temperature increases over the three time periods 1901 to 2020, 1951 to 2020 and 1981 to 2020 in °C. Temperature increases over Continental Europe are twice as large as global and three to four times larger than over the nearby midlatitude ocean. Temperature increases are particularly large since the 1980s and continue to increase into the new century.

Broadband and spectrally resolved shortwave downward and upward radiation were measured from airplanes, primarily in the lower troposphere, to investigate aerosol- and cloud-radiation interactions and to test and improve radiative transfer calculations (Wendisch et al., 1996; Wendling et al., 2002; Wendisch and Mayer, 2003; Guan et al., 2010). Vertical shortwave and longwave radiation profiles through the atmosphere have been sporadically measured in a few experiments at diverse locations worldwide (Suomi et al., 1958; Paltridge and Sargent, 1971; Yamamoto et al., 1995; Asano et al., 2004; Philipona et al., 2012; Kräuchi and Philipona, 2016; Philipona et al., 2020). Despite all these studies, the incoming and outgoing solar and thermal radiation on Earth and their relation to climate change are still a wide-reaching scientific challenge.

Here, we experimentally demonstrate that although it is now widely accepted that the Earth's surface warming is too rapid to be linked to changes in solar activity, solar radiation has played a crucial role in the rapid temperature increase observed over continents in recent decades. We present surface radiation measurements that show that over Central Europe, where the temperature increase over recent decades is more than twice as large than the global average warming, solar radiation absorbed at the surface increased 30 percent more than the rising downwardthermal greenhouse radiation and can therefore not be ignored as strongest and crucial driver of the recent rapidly increasing warming observed over continental Europe.

2 Temperature and radiation date used for these analyses

The temperatures over larger Europe shown in Fig. 1, as well as Global and Central Europe temperatures shown in Fig. 2 were determined using HadCRUT5 analysis data from the Climate Research Unite of the University of East Anglia and the Met Office (Jones et al., 1999; Osborne et al., 2021). In the following figures and tables temperature-, sunshine duration- and radiation data are all from MeteoSwiss.

Since global temperature noticeably increases since the beginning of the 20th century, we have chosen the

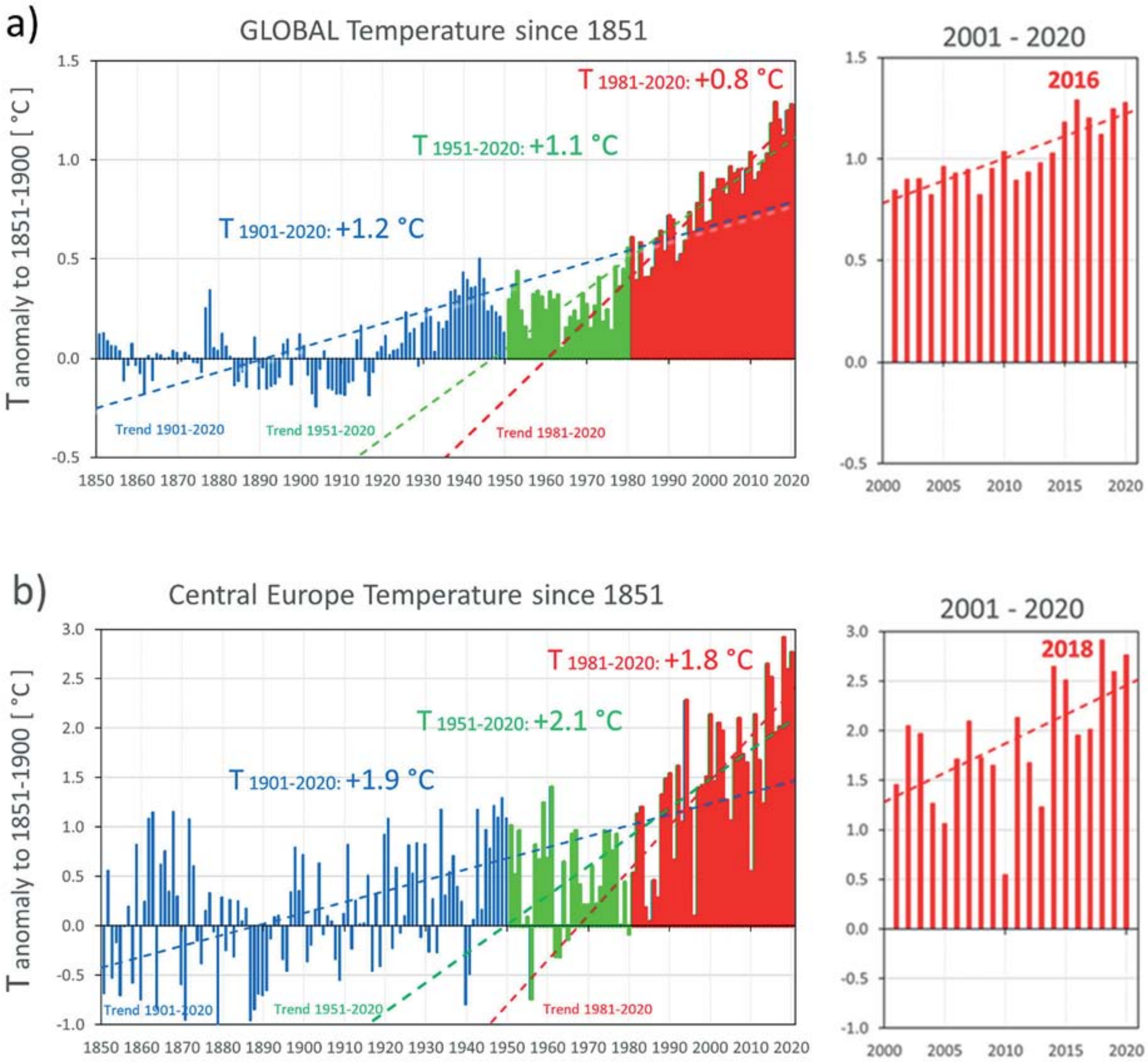

Figure 2: Global and Central Europe (45–50 N / 5–15 E) temperature anomalies from 1851 to 2020. Anomalies are referenced to the 1851 to 1900 average and temperature trends are indicated for the three time periods. Global temperature (a) shows the six warmest years all between 2015 and 2020. In Central Europe (b) five of the warmest years occur after 2014, with 2018 the warmest year ever measured (right graphs).

time period from 1901 to 2020 to emphasize specific temperature changes over the last 120 years. The second period 1951 to 2020 shows how temperature stays rather constant from 1951 to 1980 but further on increases. Most important however, is the third period from 1981 to 2020, which shows in detail the increase in temperature and the different forcings that are responsible for the observed rapid warming over the recent decades.

To demonstrate the rapid warming in Europe, we compared temperature and sunshine hours, as well as solar and thermal radiation measurements of 20 MeteoSwiss stations located in the (45–50 N / 5–15 E) pixel of Central Europe. Fig. 3 shows the 20 stations well distributed over Switzerland, north, and south of the Alps, at altitudes between 273 m (Lugano) and 3580 m (Jungfraujoch) a.s.l. The average altitude of the ten lowland stations is approximately 500 m a.s.l., and they are all from the MeteoSwiss National Basic Climatological Network (Swiss NBCN) (Seiz and Foppa, 2011). Four of these stations (Geneva, Bern, Basel, and Zurich) have specifically checked temperature and sunshine duration data, which are carefully treated by MeteoSwiss. The average altitude of the ten alpine stations is approximately 2000 m a.s.l., and six of these stations are from the NBCN network.

Fig. 1 shows a temperature increase in Central Europe from 1981 to 2020 of 1.8 °C using HadCRUT5 data. Over the same period Fig. 5 shows a temperature increase of 1.9 °C using MeteoSwiss data at 10 Swiss stations at about 500 m a.s.l. The reliability of the data sets used is furthermore demonstrated by the close correlation of sunshine duration and the shortwave net radiation shown in Fig. 5a) and b), which are both individually measured with different sets of instruments.

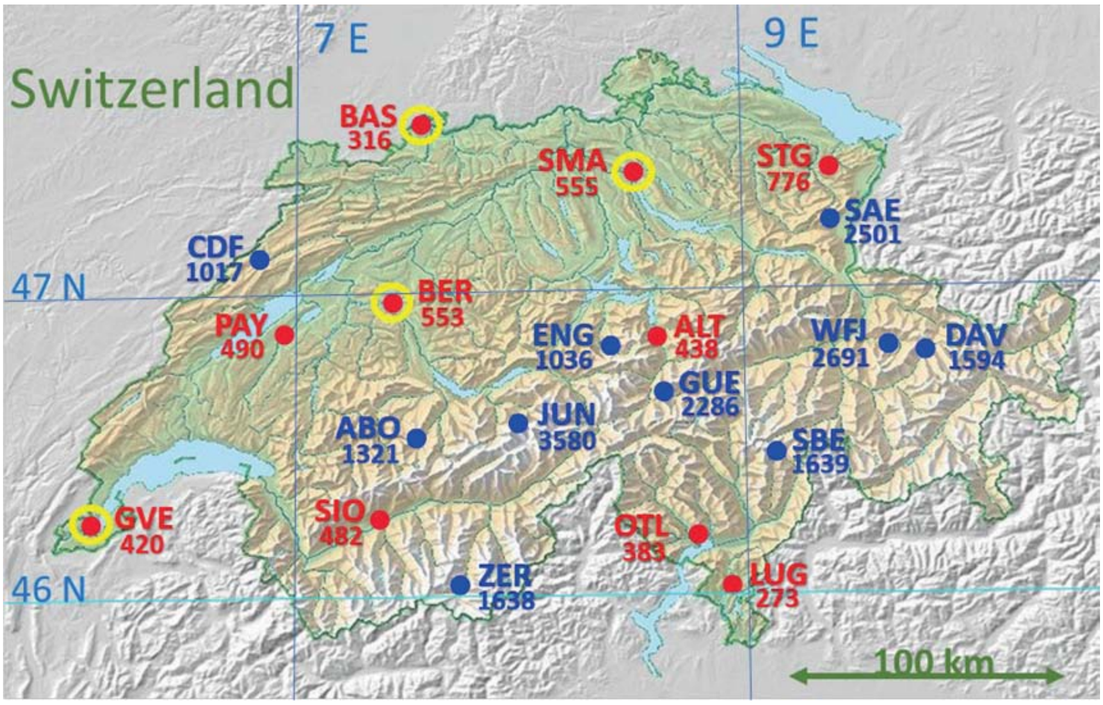

Figure 3: Twenty meteorological stations to investigate temperature and radiation in Switzerland. Red dots show the ten lowland stations at the average altitude of 500 m a.s.l. Blue dots show the ten alpine stations at the average altitude of 2000 m a.s.l. The four stations with yellow circles, GVE Geneva, BER Bern, BAS Basel and SMA Zurich on the Swiss plateau, have specifically checked data series.

3 Enhanced increase of temperature over continents

Temperature records over Europe and its surroundings show that temperature increases considerably more over land than over ocean. Fig. 1 shows that over the last four decades, temperature has increased considerably more over land pixels compared to global average warming. In the Arctic, rapid warming is reinforced by decreasing albedo, and hence, rising surface absorption of solar radiation during the summer months. Over all investigated time periods, the warming was three to four times larger over land than over nearby mid-latitude ocean pixels. The values shown for the global and northern hemispheres and the individual pixels were calculated using a linear regression method over the different time periods.

The global increase in temperature and in Central Europe (45–50 N / 5–15 E) since the mid-nineteenth century is shown in Fig. 2a and Fig. 2b, where the individual years are compared to the average temperature measured between 1851 and 1900. The graphs show that since 1920, most of the years have been warmer than the 1851 to 1900 average. The strongest increase, however, started in the 1980s, and over the last four decades, temperature increased globally by +0.8 °C and more than twice as much over land in Central Europe. The global temperature increase (Fig. 2a) is very consistent, with the warmest year 2016 reaching +1.29 °C above the 1851 to 1900 average, and the six warmest years ever measured were all between 2015 and 2020 (Press Office, 2021). In Central Europe (Fig. 2b), the variability is larger, but still five of the warmest years occur after 2014, with 2018 the warmest year that reaches +2.91 °C above the 1851 to 1900 average.

4 More clear skies reinforce temperature rise

Sunshine duration was measured from the beginning of Swiss meteorological measurements in 1864. Fig. 4 shows the evolution of the total annual sunshine duration (*ASD*) in hours [h] and temperature (*T*) in [°C] over 1901 to 1950 (Fig. 4a) and 1951 to 2020 (Fig. 4b) at the four specifically checked NBCN stations, which represent the Swiss lowland at about 500 m a.s.l. From 1901 to 1950, the linear regression method shows a temperature rise of +1.1 °C. At the same time, the sunshine duration *ASD*, shown in purple, increased by only +56 h. The data clearly show that from the beginning of the century to the 1950s, temperature increased more or less independently of sunshine duration (Scherrer and Begert, 2019).

In contrast, Fig. 4b shows that from 1951 to 2020, temperature strongly increased by +2.4 °C in tight relation with annual sunshine duration, which increased by +250 h over the last seven decades (Van den Besselaar et al., 2015). From the 1950s, temperature as well as *ASD* show a decrease, and thereafter a strong re-increase from the 1980s to the present. The decrease in temperature and *ASD* since the 1950s was caused by heavy atmospheric pollution during the rapid economic

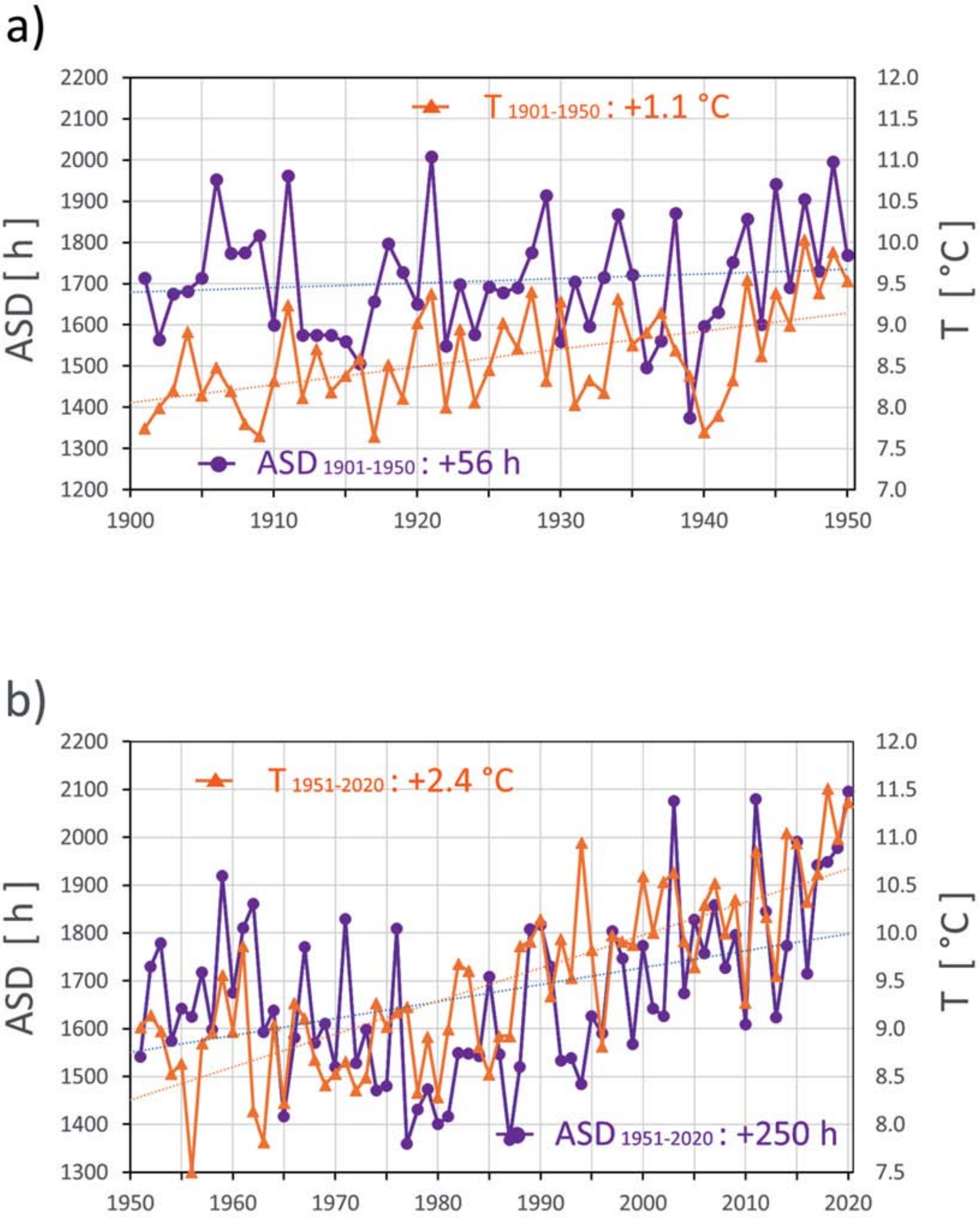

Figure 4: Annual sunshine duration and temperature from 1901 to 2020 in Switzerland. The data in the two graphs represent averages over the four specifically checked MeteoSwiss stations Geneva, Bern, Basel and Zurich at about 500 m a.s.l. Graph a) shows that from 1901 to 1950 temperature *T* increases more than annual sunshine duration *ASD*. Graph b) on the other hand from 1951 to 2020 *T* and *ASD* are strongly related and first decrease up to the 1980s and thereafter strongly increase.

development after the Second World War, which resulted in the global dimming phase up to the 1980s (Ramanathan et al., 2001). The increase from the 1980s to the end of the century is in line with the brightening phase observed in Europe (Wild et al., 2005), with the reduction of air pollution and clearing of the atmosphere through stringent emission control and regulations (Ruckstuhl et al., 2008). Surprisingly, however, *ASD* continues to increase in the new century even after the cleaning of the atmosphere. This sustained *ASD* increase is more like a positive greenhouse warming feedback because rising surface temperatures reduce cloud formation and lead to clearer skies that rise sunshine hours and lead to more solar radiation reaching the Earth's surface (Tang et al., 2012).

5 Solar and thermal greenhouse radiation increase

The main energy source of planet Earth is solar radiation, which is partly absorbed at its surface. By this the Earth surface reaches a certain temperature and emits thermal longwave radiation into the sky. This thermal longwave upward radiation is in part lost into space, but part of it is absorbed in the atmosphere by clouds and greenhouse gases and is thereby heating the atmosphere. The warm atmospheric greenhouse gases emit longwave radiation in all direction, and part of it is coming back to the Earth surface as thermal longwave downward radiation or thermal "greenhouse" radiation. With rising anthropogenic greenhouse gases in the atmosphere (CO_2, CH_4, N_2O and others), the thermal greenhouse radiation increases at the surface.

However, as sunshine duration also increases, it is of interest to know the effect this sunshine-related positive greenhouse warming feedback has on increasing solar radiation, and hence, global warming. Global solar radiation has been measured with pyranometers at Swiss NBCN stations since the 1970s. In the radiation budget below, the solar shortwave net radiation (*SNR*) is shown, which is the global minus the reflected, or the effective surface absorbed solar radiation. Thermal or longwave downward radiation (*LDR*) has been measured using pyrgeometers at MeteoSwiss stations since the 1990s (Marty et al., 2002). For the first years since 1981, longwave radiation values were calculated using a well-established relationship with other meteorological parameters (Ruckstuhl et al., 2007). Finally, the total absorbed radiation (*TAR*) is the sum of *SNR* and *LDR*, and hence, the total incoming solar and thermal radiation heating the Earth's surface. All radiation components are shown in [$\mathrm{W\,m^{-2}}$].

In Fig. 5, we compare the temperature increase from 1981 to 2020, with a) annual sunshine duration *ASD*, b) solar shortwave net radiation *SNR*, c) thermal longwave downward radiation *LDR*, and d) total absorbed radiation *TAR*, all averaged over the ten lowland stations at 500 m a.s.l. (left), and over the ten alpine stations at 2000 m a.s.l. (right).

The temperature increase of +1.9 °C from 1981 to 2020 at lowlands in Switzerland (Fig. 5a) is similar to the increase of +1.8 °C in the Central Europe pixel (Fig. 1). The annual sunshine duration *ASD* increased by +354 h over the four decades. This strong *ASD* increase at lowlands is more than three times larger than the +106-h increase at the ten alpine stations, although the temperature increase of +1.6 °C is only modestly lower in the Alps. The strong increase in *ASD* in the lowlands is on the one hand related to the strong reduction of air pollution during the brightening period after the 1980s (Philipona et al., 2009). On the other hand, high humidity, large fog, and low stratus clouds in lowlands are apparently more affected by rising temperatures (Scherrer and Appenzeller, 2014), than the less cloudy and drier atmosphere in the Alps (Rottler et al., 2019). Hence, the resulting slightly negative elevation-dependent warming trend over the Alps is seemingly related to a lower increase in *ASD* at higher altitudes (Tudoroiu et al., 2016).

The surface-absorbed solar radiation *SNR* (Fig. 5b) increased with temperature, similar to *ASD* at both altitude levels. All the years that show high ASD show also high SNR (1985, 1990, 1997, 2003, 2011, 2015, 2020), and demonstrate high correlation between ASD and SNR. The strong temperature rise follows *SNR* particularly well since the hot summer of 2003, and *ASD* and *SNR* both follow similar variations, but the rising temperature even more follows *SNR* than *ASD* at both altitudes.

The overall increase in longwave downward radiation *LDR* at the surface (Fig. 5c) similarly follows the temperature increase as *SNR*. Looking at the individual years, one sees that the ups and downs of *SNR* and *LDR* are often opposite. The warm year 1994 was clearly due to strong *LDR* and weak *SNR*, whereas the warm year 2003 was due to strong *SNR* and weak *LDR*. The two cold years 1996 and 2010, on the other hand, show weak *SNR* and *LDR*, whereas the warmest year 2018 shows strong *SNR* and *LDR* and shows the highest total absorbed radiation *TAR* ever measured.

TAR consistently follows the temperature increase after the turn of the century (Fig. 5d) and is in almost perfect agreement with temperature over the last decade. In fact, correlation coefficients calculated for the period 2001 to 2020, in which the *LDR* values were instrumentally measured, show that the correlation with temperature always increases from *ASD* (0.65) to *SNR* (0.71) to *LDR* (0.73) to *TAR* (0.91) for the lowland measurements, and from *ASD* (0.52) to *SNR* (0.60) to *LDR* (0.61) to *TAR* (0.85) for the alpine measurements. Hence, the correlation coefficients of *SNR* and *LDR* are similar, and together they culminate in the highest correlation coefficients of the total absorbed radiation *TAR* at lowland and alpine stations.

6 Discussion

Temperature measurements over larger Europe show that the temperature rise since the beginning of the twentieth century is three to four times larger over land surfaces than over nearby mid-latitude sea surfaces. In addition, the enhanced rapid warming since the early 1980s is at least twice as large over continental Europe compared to the global average warming. In situ radiation measurements in Central Europe show that the increase in solar *SNR* and thermal *LDR* radiation reveal high correlation with temperature and are clearly the driving forces of surface warming.

The increase in temperature and radiation parameters over the last four decades in Central Europe is shown in more detail in Table 1a), which provides information on the different driving forces and their impact on the observed climate change in lowland Switzerland. In the first part, linear increases per decade are shown for the different parameters over four time periods. The linear increases show that temperature rises by almost 0.5 °C per decade since the 1980s, and that the warming reached a 1 °C linear increase over the last decade. In addition to temperature, sunshine duration *ASD*, solar *SNR* and thermal *LDR* radiation all showed a general

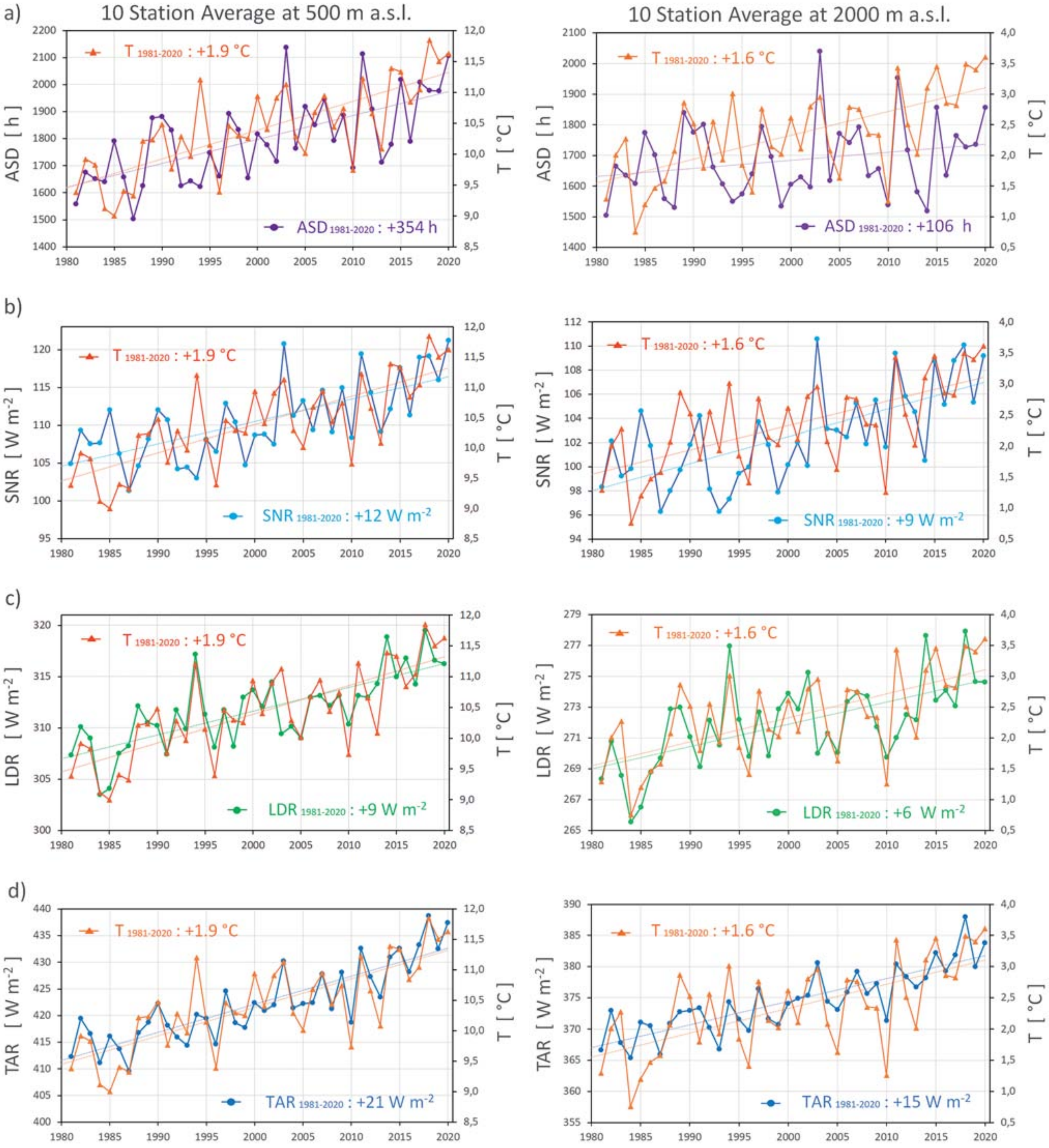

Figure 5: Temperature, annual sunshine duration and radiation components at two altitudes from 1981 to 2020. The graphs on the left show averages over the ten lowland stations at 500 m a.s.l., and on the right averages over the ten alpine stations at 2000 m a.s.l., a) Annual sunshine duration *ASD* and temperature *T* over the four decades, b) Shortwave net radiation *SNR* and temperature *T*, c) Longwave downward radiation *LDR* and temperature *T*, d) Total absorbed radiation *TAR* and temperature *T*.

increase over the four time periods, and a strong increase in the last decade. Linear increases are also given for the total absorbed radiation *TAR*, as well as for the thermal surface-emitted longwave upward radiation (*LUR*) and the total net radiation (*TNR*), which all show rising trends over the four time periods. Linear increases over the full time period from 1981 to 2020 are shown in a separate line below for all parameters. The first five numbers are basically the same as shown in Fig. 5 (left), with *SNR* larger than *LDR* and hence the stronger driver. *TAR* increased by $21\,\mathrm{W\,m^{-2}}$, whereas *TNR* increased by almost $13\,\mathrm{W\,m^{-2}}$ in lowland Switzerland over the last four decades, and this primarily due to rising solar radiation reaching the Earth's surface.

Table 1: Temperature, annual sunshine duration and radiation components, and their linear increases over different time periods from 1981 to 2020. a) averaged over the ten lowland stations at average altitude of 500 m a.s.l., b) averaged over the ten alpine stations at average altitude of 2000 m a.s.l.

a) 10 Station Average at 500 m a.s.l.

Linear Increase over Time Period per Decade	T [°C]	ASD [h]	SNR [W m^{-2}]	LDR [W m^{-2}]	TAR [W m^{-2}]	LUR [W m^{-2}]	TNR [W m^{-2}]	T / TAR [K / W m^{-2}]
1981–2020	+0.47	+88	+3.0	+2.3	+5.3	−2.1	+3.2	0.09
1991–2020	+0.43	+99	+4.1	+2.3	+6.4	−2.8	+3.6	0.07
2001–2020	+0.54	+79	+3.8	+3.6	+7.4	−3.3	+4.1	0.07
2011–2020	+1.02	+133	+5.6	+4.0	+9.6	−4.6	+5.0	0.11

Linear Increase over Time Period	T [°C]	ASD [h]	SNR [W m^{-2}]	LDR [W m^{-2}]	TAR [W m^{-2}]	LUR [W m^{-2}]	TNR [W m^{-2}]	T / TAR [K / W m^{-2}]
1981–2020	+1.87	+354	+11.8	+9.2	+21.0	−8.3	+12.7	0.09

b) 10 Station Average at 2000 m a.s.l.

Linear Increase over Time Period per Decade	T [°C]	ASD [h]	SNR [W m^{-2}]	LDR [W m^{-2}]	TAR [W m^{-2}]	LUR [W m^{-2}]	TNR [W m^{-2}]	T / TAR [K / W m^{-2}]
1981–2020	+0.39	+26	+2.2	+1.5	+3.7	−1.9	+1.8	0.11
1991–2020	+0.40	+33	+3.2	+1.1	+4.3	−1.9	+2.4	0.09
2001–2020	+0.60	+14	+2.7	+1.8	+4.5	−2.9	+1.6	0.13
2011–2020	+0.83	+31	+2.7	+3.8	+6.5	−3.9	+2.6	0.13

Linear Increase over Time Period	T [°C]	ASD [h]	SNR [W m^{-2}]	LDR [W m^{-2}]	TAR [W m^{-2}]	LUR [W m^{-2}]	TNR [W m^{-2}]	T / TAR [K / W m^{-2}]
1981–2020	+1.56	+106	+9.0	+5.8	+14.8	−7.5	+7.3	0.11

The same parameters are shown in Table 1b) for the ten alpine stations. The numbers show similar behavior, with the rise of *SNR* generally larger than *LDR* over the different time periods, except for the last decade. Compared to the temperature rise, which is slightly lower at high altitudes, the *SNR* and *LDR* increases are smaller, which implies that the temperature increase at higher altitudes is likely not only driven by rising radiation, but also by increased convection due to rising temperatures at lower altitudes.

In the last column of Tables 1a) and 1b), the respective surface temperature rise *T* is divided by the increase in *TAR* over the different time periods. The numbers show, that at low and high elevations, the surface temperature increases by roughly 0.1 °C or Kelvin if *TAR* increases by 1 W m^{-2}. Hence, at mid-latitudes, the temperature rise over continents follows a surface warming coefficient of roughly 0.1 K/W m^{-2}.

7 Conclusions

Our analyses of temperature and radiation measurements show that the rapid temperature rise in Central Europe, which is twice as large as global warming, is driven in part by the expected rise in thermal longwave downward radiation *LDR*, which increases due to anthropogenic greenhouse gases and the related rising greenhouse effect. However, surprising is the finding that over the last four decades annual sunshine duration *ASD* steadily and more and more increased, and that the related increase in solar shortwave net radiation *SNR* is about 30 percent larger than the thermal *LDR* increase, and hence the strongest driver of climate change in Central Europe since the 1980s. The increase in *SNR* plus *LDR* or total absorbed radiation *TAR* over the last four decades is approximately 40 percent higher at lowland than in the Alps and explains the negative elevation-dependent warming trend over the Alps. In addition, rising *T* and *TAR* show high correlation coefficients, 0.91 for the lowland and 0.85 in the Alps, which confirms the strong relationship between rising surface radiation and global warming. At lowland the temperature rise follows a surface warming coefficient of 0.09 K per W m^{-2} of rising thermal plus solar surface absorbed radiation. In the Alps the rising temperature is likely not only driven by rising radiation, but also by increased convection due to rising temperatures at lower altitudes.

Over the oceans, the ratio of surface temperature to radiation increase is likely considerably lower because thermal flow and storage conditions in sea water are much larger than over land. This temperature-stabilizing effect in surface water prevents solar radiation from increasing over the oceans. Measurements in future years will show how temperature trends and driving radiative forces evolve. With rising anthropogenic greenhouse gases, greenhouse warming and the observed sunshine-related positive greenhouse warming feedback will likely further boost the temperature increase in the coming decades over the continents.

Acknowledgments

We thank Johannes Aschauer for his assistance in preparing the data series. We are thankful for the data received from the University of East Anglia, the Met Office, and MeteoSwiss.

Data availability statement

The data can be downloaded from the University of East Anglia, the Met Office, and MeteoSwiss.

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