

Article

Mitigating Climate Warming: Mechanisms and Actions

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Abstract

To validate a positive relationship between air temperature (T) and atmospheric substances (S/G, a ratio of diffuse solar radiation to global solar radiation) found at four typical stations on the Earth, and a further investigation was conducted. Based on the analysis of long-term solar radiation, atmospheric substances, and air temperature at 29 representative stations of baseline surface radiation network (BSRN) in the world, the relationships and the mechanisms between air temperature and atmospheric substances were studied in more detail. A universal non-linear relationship between T and S/G was still found, which supported the previous relationship between T and S/G. This further revealed that a high (or low) air temperature is strongly associated with large (or small) amounts of atmospheric substances. The mechanism is that all kinds of atmospheric substances can keep and accumulate solar energy in the atmosphere and then heat the atmosphere, causing atmospheric warming at the regional and global scales. Therefore, it is suggested to reduce the direct emissions of all kinds of atmospheric substances (in terms gases, liquids and particles, and GLPs) from the natural and anthropogenic sources, and secondary formations produced from atmospheric compositions via chemical and photochemical reactions (CPRs) in the atmosphere, to slow down the regional and global warming through our collective efforts, by all mankind and all nations. Air temperature increased at most BSRN stations and many sites in China, and decreased at a small number of BSRN stations during long time scales, revealing that the mechanisms of air temperature change were very complex and varied with region, atmospheric substances, and the interactions between solar radiation, GLPs, and the land.

Keywords: global warming; global solar radiation; air temperature; atmospheric substances; climate change



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1. Introduction

Solar radiation, as the most important energy source for the Earth, controls the changes in atmospheric substances in the form of gases, liquids, and particles (GLPs) and the movements of the atmosphere, as well as climate change. These GLPs come from (1) direct emissions from all kinds of sources, including greenhouse gases (GHGs, CO₂, N₂O, CH₄, etc.), non-GHGs (NO₂, SO₂, O₃, anthropogenic and biogenic volatile organic compounds (AVOCs and BVOCs), aerosols, etc.), (2) and indirect production through chemical and

photochemical reactions (CPRs) [1–4]. Global warming appears in the most representative and vulnerable regions/sites (the Antarctic, Arctic, and Tibetan Plateau, the world's third pole) and many sites in China during the 20th century and has been reported by the Intergovernmental Panel on Climate Change (IPCC) and many studies [5–12]. Some possible mechanisms are proposed, including solar radiation, astronomical factors, changing oceanographic and atmospheric circulations, regional air–sea-ice feedback, etc. Among them, anthropogenic increases in GHGs are considered a common cause [6,13–29]. Are there any other important and basic reasons behind the phenomenon of global warming or climate change? It is still of great importance to further investigate the mechanisms associated with regional and global climates and climate change. Therefore, solar radiation and its transfer (absorption and scattering in the atmosphere and reflections at the top of the atmosphere (TOA) and the surface) and the link between air temperature and atmospheric substances should be fully studied using surface- and satellite-based observations and model estimations.

It has been found that there is a strong positive correlation between air temperature (T) and atmospheric substances (S/G) at four representative sites on the Earth, and the mechanisms related to the complicated processes are discussed and reported in references [13–25]. The aim of this study is to further investigate this relationship between T and S/G at more typical sites on the Earth using reliable hourly data collected at the Baseline Surface Radiation Network (BSRN), which provides unified high-quality reference measurements of solar radiation with unified standards for routine maintenance and regular calibration [26–28]; to explore and validate mechanisms under several atmospheric situations, i.e., (1) different S/G levels (idealized with $S/G < 0.5$ and 0.6 , and all sky (i.e., realistic) conditions with $S/G = 0–1.0$), and (2) different solar altitudes, corresponding to different levels of (1) atmospheric substances and (2) global solar radiation, respectively. Considering that (1) solar radiation is evidently attenuated by atmospheric GLPs, the large observational errors usually appear at low solar radiations, especially at high GLP loads (e.g., clouds, aerosols, sand storms, precipitation, and air pollutants), and (2) solar radiation measurements are strongly influenced by solar altitudes, i.e., larger cosine errors occur at lower solar altitudes; and finally to propose suggestions to mitigate regional and global climate warming effectively.

2. Data and Methodology

2.1. Data

Solar radiation data (global, direct, and diffuse solar radiation on a horizontal plane, described as G , D , and S (Wm^{-2}), respectively) were obtained from the sites of the BSRN (<https://bsrn.awi.de>, accessed on 10 October 2024). Meteorological parameters (i.e., air temperature, T , $^{\circ}\text{C}$) were also obtained from the BSRN stations. The criteria for the data selection were that the time scale was more than 7 years with continuous hourly observations, and 29 stations were selected and used in the analysis [26]. The annual statistics of 29 stations were 17.2 on average, 16 for the median, and 7 and 30 for the minimum and maximum, respectively. As an example, we briefly report the sampling numbers (n) of hourly solar radiation and air temperature data used in the analysis of 29 stations: 7112, 51,040, and 25,275 (minimum, maximum, average, the same hereinafter) for $h > 10^{\circ}$ and 8469, 54,282, and 27,858 for all h under $S/G < 0.5$ conditions; 7759, 55,512, 28,931 for $h > 10^{\circ}$ and 9559, 60,524, 32,570 for all h under $S/G < 0.6$ conditions; 16,668, 98,768, 52,246 for $h > 10^{\circ}$ and 18,840, 113,445, and 63,032 for all h under all sky conditions ($S/G = 0–1.0$).

As for the instruments, taking Dome C ($75^{\circ}06' \text{ S}$, $123^{\circ}21' \text{ E}$, 3233 m) in the Antarctic as an example, the observational instruments are introduced briefly. Global solar irradiance and diffuse horizontal irradiance were measured by secondary standard unshadowed

and shadowed pyranometers, respectively (model CM22, Kipp & Zonen Inc., Delft, The Netherlands). Direct beam irradiance was measured by a pyrliometer (CH1, Kipp & Zonen Inc., Delft, and The Netherlands). All radiation sensors should be calibrated every 2 years according to the unified BSRN protocols [27,28]. Meteorological variables, such as air temperature and relative humidity (RH) were obtained from the IPEV/PNRA Project “Routine Meteorological Observation at Station Concordia”—<http://www.climantartide.it> (accessed on 10 October 2024). The surrounding region of the Dome C site is covered by surface snow, and the air temperature varies from $-80\text{ }^{\circ}\text{C}$ to $-20\text{ }^{\circ}\text{C}$. A minimum air temperature of $-98\text{ }^{\circ}\text{C}$ has been observed. The atmosphere is cold, dry, clear, and clean [29–32]. The detailed information for the instruments at other BSRN stations can be seen on the website (<https://bsrn.awi.de>, accessed on 10 October 2024). The BSRN provides high-quality measurements of downwelling solar and terrestrial radiation (LR001); most stations also measure upwelling components (LR003) in order to define the surface radiation balance.

2.2. Methodology

To fully understand the basic characteristics of solar radiation and air temperature at the selected BSRN stations under all skies (cloudiness ranged from 0 to 1), observed hourly $G > 20\text{ W m}^{-2}$ (avoiding the large cosine error of the sensor at low solar altitudes), and all other corresponding observed data were used to calculate the daily, monthly, and annual values. The extreme hourly values of solar radiation (G , S , and D) and the ratio S/G (dimensionless, diffuse radiation/global radiation, representing atmospheric substances in the whole atmospheric column) > 1.0 were excluded. The data criterion that the observed solar radiation should be in the range of 0–1.2 times the extraterrestrial radiation was used [14]. The selected stations and their main descriptions are shown in Table 1.

Table 1. The 29 BSRN stations and their characteristics.

Station Full Name	Abbreviation	Location	Latitude	Longitude	Elevation	First Dataset in Archive	Surface Type	Topography Type	Rural/Urban	Köppen–Geiger Classification
Alert	ALE	Canada, Lincoln Sea	82.5	−62.4	127	16 August 2004	tundra	hilly	rural	ET (Polar, tundra)
Barrow	BAR	AK, USA	71.3	−156.6	8	1 January 1995	tundra	flat	rural	ET (Polar, tundra)
Billings	BIL	OK, USA	36.6	−97.5	317	1 June 1993	grass	flat	rural	Cfa (Temperate, no dry season, hot summer)
Boulder	BOU	CO, USA	40.1	−105.0	1577	1 January 1992	grass	flat	rural	BSk (Arid, steppe, cold)
Cabauw	CAB	Netherlands	52.0	4.9	0	1 December 2005	grass	flat	rural	Cfb (Temperate, no dry season, warm summer)
Carpentras	CAR	France	44.1	5.1	100	1 August 1996	cultivated	hilly	rural	Csa (Temperate, dry summer, hot summer)
Chesapeake Light	CLH	North Atlantic Ocean, USA	36.9	−75.7	37	1 June 2000	water, ocean	flat	rural	NaN (NaN)
Cener	CNR	Spain, Navarra	42.8	−1.6	471	1 July 2009	asphalt	mountain valley	urban	Cfb (Temperate, no dry season, warm summer)
Darwin	DAR	Australia	−12.4	130.9	30	1 June 2002	grass	flat	rural	Aw (Tropical, savannah)
Concordia Station, Dome C	DOM	Antarctica	−75.1	123.3	3233	1 January 2006	glacier, accumulation area	flat	rural	EF (Polar, frost)
Fukuoka	FUA	Japan	33.6	130.4	3	1 April 2010	asphalt	flat	urban	Cfa (Temperate, no dry season, hot summer)
Gobabeb	GOB	Namibia, Namib Desert	−23.6	15.0	407	15 May 2012	desert gravel	flat	rural	BWh (Arid, desert, hot)
Georg von Neumayer	GVN	Antarctic, Dronning Maud Land	−70.7	−8.3	42	1 January 1992	iceshelf	flat	rural	NaN (NaN)
Ishigakijima	ISH	Japan	24.3	124.2	5.7	1 April 2010	asphalt	flat	rural	Af (Tropical, rainforest)

Table 1. Cont.

Station Full Name	Abbreviation	Location	Latitude	Longitude	Elevation	First Dataset in Archive	Surface Type	Topography Type	Rural/Urban	Köppen–Geiger Classification
Izaña	IZA	Spain, Tenerife	28.3	−16.5	2372.9	1 March 2009	rock	mountain top	rural	Csb (Temperate, dry summer, warm summer)
Kwajalein	KWA	Marshall Islands	8.7	167.7	10	1 March 1992	water, ocean	flat	rural	Af (Tropical, rainforest)
Lindenberg	LIN	Germany	52.2	14.1	125	1 September 1994	cultivated	hilly	rural	Dfb (Cold, no dry season, warm summer)
Langley Research Center	LRC	VA, USA	37.1	−76.4	3	1 December 2014	grass	flat	urban	Cfa (Temperate, no dry season, hot summer)
Momote	MAN	Papua New Guinea	−2.1	147.4	6	1 September 1996	grass	flat	rural	Af (Tropical, rainforest)
Minamitorishima	MNM	Japan, Minami-Torishima	24.3	154.0	7.1	1 April 2010	water (ocean)	flat	rural	NaN (NaN)
Nauru Island	NAU	Nauru	−0.5	166.9	7	1 November 1998	rock	flat	rural	Af (Tropical, rainforest)
Ny-Ålesund	NYA	Norway, Spitsbergen	78.9	11.9	11	1 August 1992	tundra	mountain valley	rural	ET (Polar, tundra)
Palaiseau, SIRTa Observatory	PAL	France	48.7	2.2	156	1 May 2003	concrete	flat	urban	Cfb (Temperate, no dry season, warm summer)
Payerne	PAY	Switzerland	46.8	6.9	491	1 September 1992	cultivated	hilly	rural	Dfb (Cold, no dry season, warm summer)
Petrolina	PTR	Brazil	−9.1	−40.3	387	1 December 2006	concrete, since 2015: shrub	flat	rural	BSh (Arid, steppe, hot)
Sonnblick	SON	Austria	47.1	13.0	3108.9	1 January 2013	rock	mountain top	rural	ET (Polar, tundra)
South Pole	SPO	Antarctica	−90.0	−24.8	2800	1 January 1992	glacier, accumulation area	flat	rural	EF (Polar, frost)
Syowa	SYO	Antarctica	−69.0	39.6	29	1 January 1994	sea ice	hilly	rural	NaN (NaN)
Tateno	TAT	Japan	36.1	140.1	25	1 February 1996	grass	flat	urban	Cfa (Temperate, no dry season, hot summer)

To further validate whether this phenomenon was also common at other sites on the Earth and to investigate the possible mechanism of climate warming, more extensive studies on some typical BSRN stations on the northern and southern hemispheres were conducted, as BSRN stations can provide high-quality observational data. Atmospheric substances directly and indirectly influence physical, chemical, and biological processes, and the relationship between T and S/G. Then, S/G values lower than 0.5 and 0.6 (as representatives of relative clear atmosphere, compared to higher S/G values) were used firstly. As the measurement error of observed solar radiation is influenced by solar altitude (h, degree), solar altitudes greater than 5°, 10°, 15°, and 20° were also selected.

For data analysis, hourly values were used to obtain daily averages. Based on the daily averages, the monthly average can be calculated. Finally, annual means were determined from monthly averages.

3. Results

3.1. A Strong Positive Relationship Between T and GLPs Under Relatively Clear Sky Conditions ($S/G < 0.5$ and $S/G < 0.6$)

One previous study determined a strong positive relationship between the annual average of air temperature and atmospheric substances (represented by S/G) ($T = 66.85 \times \ln(S/G) + 39.89$, R (correlation coefficient) = 0.974) at four representative stations on the Earth (two polar sites, one middle-latitude site, and one low-latitude site, namely Sodankylä in the Arctic (67.367° N, 26.630° E, 184 m), Dome C in the Antarctic, Ankara (39°58′21.7″ N, 32°51′49.3″ E, 890 m) in Türkiye, and Qianyanzhou (26°44′48″ N, 115°04′13″ E, 110.8 m) in China) [25] under all sky conditions, indicating that an internal interaction/link existed between net energy (kept in the atmospheric substances such as gases, liquids and solids, i.e., the energy at the top of the atmosphere—the corresponding

value at the surface) and all kinds of GLP substances in the atmosphere, i.e., more atmospheric substances in the atmosphere will lead to a higher air temperature (or climate warming), and vice versa.

The most representative 26 stations were selected for the analysis, without the consideration of three stations (GOB, ISH, and IZA, representing desert gravel, asphalt, and rock surfaces, respectively) because of their poor, i.e., insufficient, representativeness, and due to not being the main focus of our study; although, these three stations met the above data selection criteria. According to the hourly values at 26 out of 29 BSRN stations, the annual mean values in multiple years of T and S/G were analyzed and their relationships are shown in Figures 1 and 2. The numbers of sampling point (n) hourly values used in the analysis at 26 stations, for two situations of S/G, < 0.5 and < 0.6 , are given in Tables 2 and 3. The error analyses were conducted using the equations displayed in Figures 1 and 2 and the partial derivative. The maximum relative bias of T was estimated to be $\pm 11.3\%$, according to the relative biases of global and direct solar radiation of 8.0% and 3.3%, respectively [33]. Clear positive relationships were also found between T and S/G for situations where S/G was < 0.5 and < 0.6 . The higher the solar altitude, the stronger the correlations (R) in the relationship between T and S/G. The correlations between T and S/G at S/G < 0.6 were larger than the corresponding ones at S/G < 0.5 at different solar altitudes, implying that the sample number is an important factor influencing the relationships under relatively clean atmosphere conditions (i.e., S/G < 0.6), and S/G < 0.6 was more representative of relatively clear atmospheric conditions. Therefore, the evident relationships between T and S/G were still found in the most representative BSRN stations, covering some previously representative sites on the Earth. This further confirmed that the atmospheric GLPs are a significant factor in (1) keeping the atmospheric internal energy (via absorbing and scattering global solar radiation) that heats the atmosphere (causing climate warming), and (2) controlling the relationship between T and S/G [25].

Table 2. The sampling number (n) for hourly values at 26 stations at different solar altitudes ($h > 5^\circ$, 10° , 15° , 20° , and all altitudes) (S/G < 0.5).

Station (Abbr.)	$h > 5^\circ$	$h > 10^\circ$	$h > 15^\circ$	$h > 20^\circ$	all
ALE	8198	7112	5437	3231	8469
BAR	11,631	10,265	8451	6624	11,817
BIL	53,574	51,040	47,511	43,653	54,282
BOU	38,292	36,125	33,856	30,390	39,446
CAB	20,514	19,530	17,592	15,218	20,686
CAR	52,251	49,383	45,082	40,193	53,754
CLH	27,930	26,716	24,933	22,843	28,621
CNR	22,063	20,828	19,428	17,560	22,552
DAR	30,137	29,023	27,680	26,251	30,165
DOM	33,298	26,620	20,578	15,362	36,139
FUA	16,516	16,178	15,414	14,531	16,550
GVN	30,675	25,600	20,929	16,444	33,828
KWA	20,397	20,227	19,696	19,270	20,442
LIN	33,388	31,812	28,272	25,179	33,681

Table 2. *Cont.*

Station (Abbr.)	h > 5°	h > 10°	h > 15°	h > 20°	all
LRC	16,534	15,779	14,706	13,488	16,847
MAN	25,130	24,596	24,316	23,013	25,233
MNM	29,361	28,732	27,400	25,551	29,512
NAU	30,160	29,338	28,957	27,888	30,298
NYA	24,520	21,164	15,340	10,556	25,024
PAL	22,463	21,444	19,386	17,039	22,769
PAY	43,132	41,059	38,379	34,077	43,540
PTR	10,803	10,456	9957	9242	11,065
SON	12,327	11,263	9913	8096	13,154
SPO	35,387	31,561	250,39	159,99	36,242
SYO	30,856	26,149	21,655	17,472	33,900
TAT	39,228	37,133	35,224	31,731	39,641

Table 3. Same as Table 2, but for S/G < 0.6.

Station (Abbr.)	h > 5°	h > 10°	h > 15°	h > 20°	all
ALE	9060	7759	5885	3491	9559
BAR	13,653	11,653	9495	7454	14,105
BIL	58,809	55,512	51,214	46,949	60,524
BOU	42,123	39,341	36,766	32,930	44,037
CAB	20,514	19,530	17,592	15,218	20,686
CAR	56,453	52,916	48,047	42,691	58,993
CLH	30,891	29,247	27,168	24,773	32,087
CNR	24,878	23,288	21,627	19,455	25,740
DAR	33,909	32,099	30,471	28,865	34,154
DOM	34,724	27,535	21,209	15,776	38,270
FUA	19,833	19,166	18,070	16,955	19,987
GVN	33,387	27,651	22,518	17,671	37,750
KWA	23,721	23,319	22,405	21,763	23,863
LIN	40,013	37,555	33,112	29,383	40,871
LRC	18,184	17,182	15,970	14,584	18,783
MAN	29,766	28,776	28,325	26,696	30,100
MNM	32,805	31,682	29,894	27,672	33,306
NAU	34,783	33,179	32,590	31,185	35,161
NYA	27,975	23,730	17,056	11,706	29,033
PAL	26,736	25,239	22,686	19,864	27,548
PAY	49,337	46,364	43,099	37,988	50,308
PTR	12,091	11,632	11,052	10,256	12,650

Table 3. Cont.

Station (Abbr.)	$h > 5^\circ$	$h > 10^\circ$	$h > 15^\circ$	$h > 20^\circ$	all
SON	13,487	12,313	10,824	8869	14,473
SPO	38,288	33,791	26,562	16,869	39,498
SYO	33,361	28,083	23,197	18,695	37,624
TAT	45,290	42,617	40,177	36,132	46,207

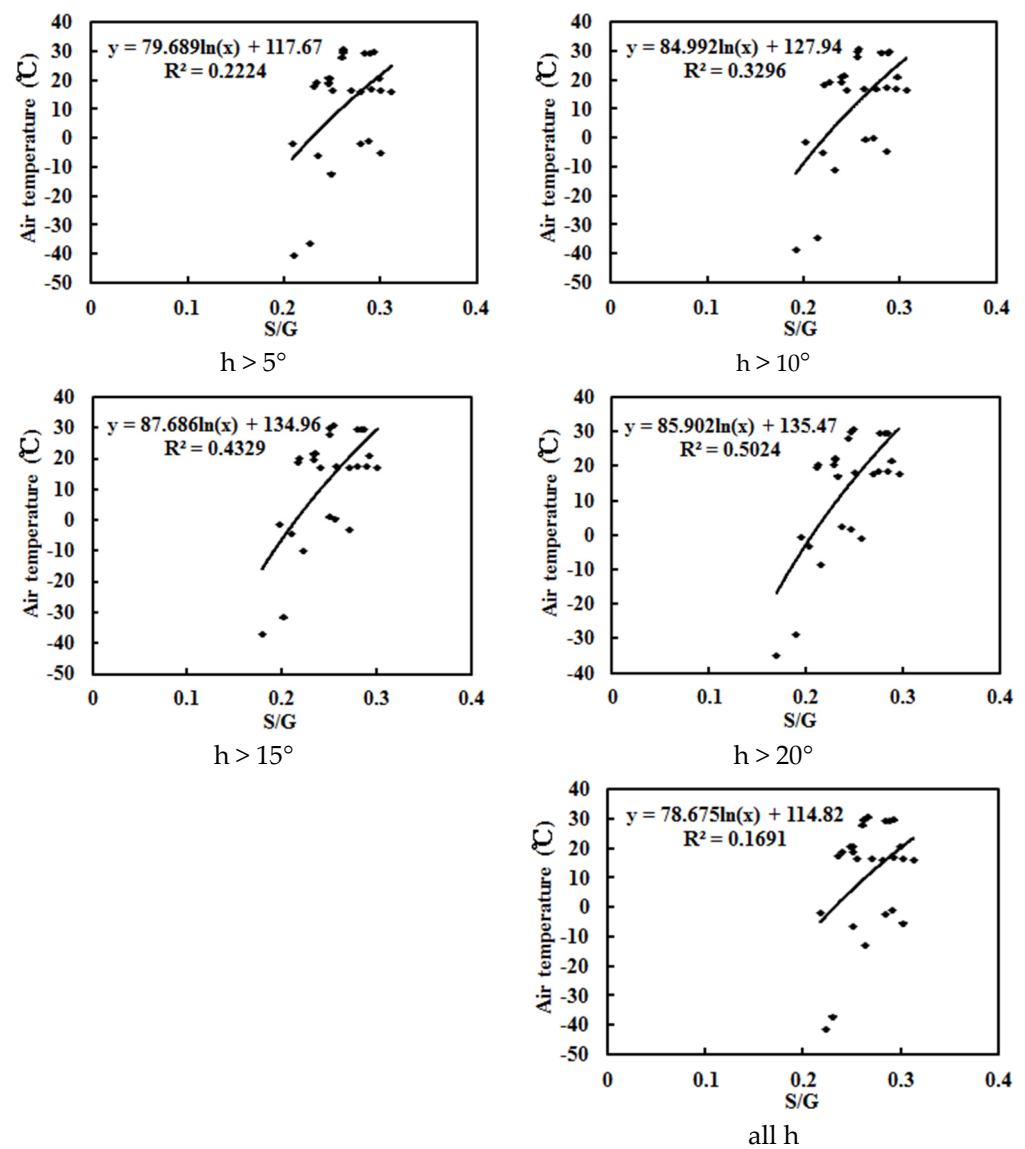


Figure 1. The relationships between annual mean T and S/G for 26 BSRN stations at different solar altitudes ($h > 5^\circ$, 10° , 15° , 20° , and all altitudes) ($S/G < 0.5$). The lines are non-linear fittings for T and S/G (described by y and x, respectively).

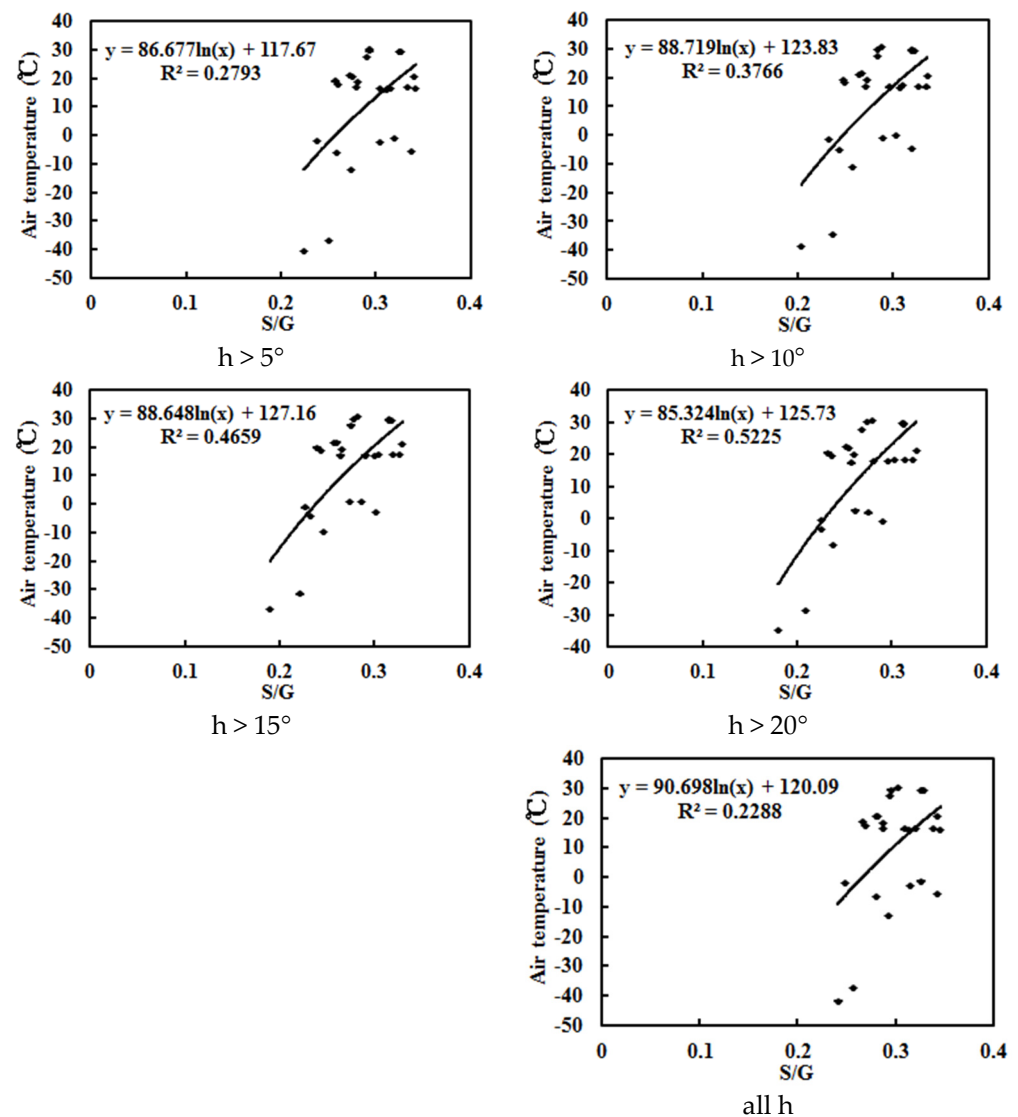


Figure 2. The relationships between annual mean T and S/G for 26 BSRN stations at different solar altitudes ($h > 5^\circ$, 10° , 15° , 20° , and all altitudes) ($S/G < 0.6$).

3.2. A Relationship Between T and Atmospheric Substances at 29 Sites Under All Skies ($S/G = 0-1.0$)

To thoroughly investigate the complex relationship between T and S/G at 29 stations under all sky conditions ($S/G = 0-1.0$)—the three stations (GOB, ISH, and IZA representing special surfaces, i.e., desert gravel, asphalt, and rock, respectively) were taken into consideration separately from the other 26 stations—the hourly mean values over multiple years (7 to 30 years) of T and S/G were also studied. Table 4 reports the sample numbers of hourly and annual values at 29 stations. Their relationships are reported in Figure 3. Compared to the situations $S/G < 0.5$ and $S/G < 0.6$, there were no evident correlations for all solar altitudes, and the negative correlations at low h ($>5^\circ$, $>10^\circ$, and all) turned to positive correlations at high h ($>15^\circ$ and $>20^\circ$), indicating the following under all sky conditions: (1) The dominant energy absorbed and scattered by GLPs in the atmosphere was not effectively used to heat the atmosphere because most of it was consumed by high concentrations of GLPs at low altitudes (which appeared, in the morning and evening, to be influenced by anthropogenic emissions) to produce new GLPs through CPRs with each other (e.g., NO_x , SO_2 , AVOCs, BVOCs, O_3 , H_2O , PM (particulate matter), aerosol optical depth (AOD), clouds, OH and excited NO_2 (NO_2^*) radicals, etc.) in the UV (290–400 nm)

and visible (VIS, 400–700 nm) regions [15–22,24,25]. (2) Very low positive correlations between T and S/G also existed at high h values (e.g., strong and sufficient global solar radiation (UV, VIS, etc.) was used in CPRs to produce new GLPs, most of which can be used effectively to warm the atmosphere). So, the high GLP loads changed or “hid to some extent” the correlations/links between T and S/G, while the low GLP loads (under a relatively clean atmosphere) are conducive to exhibiting the internal relationship clearly, compared to high GLP loads. (3) The three additional stations also caused/contributed to low correlations for the 29 stations, compared to those for the 26 stations. These three stations were GOB, ISH, and IZA with desert gravel, asphalt, and rock surfaces, and were not suitable as representative sites on the Earth. Therefore, this is a feasible way to explore/capture the internal law of nature by selecting relatively clean atmospheric conditions (i.e., low GLPs, together with high solar radiation and air temperature).

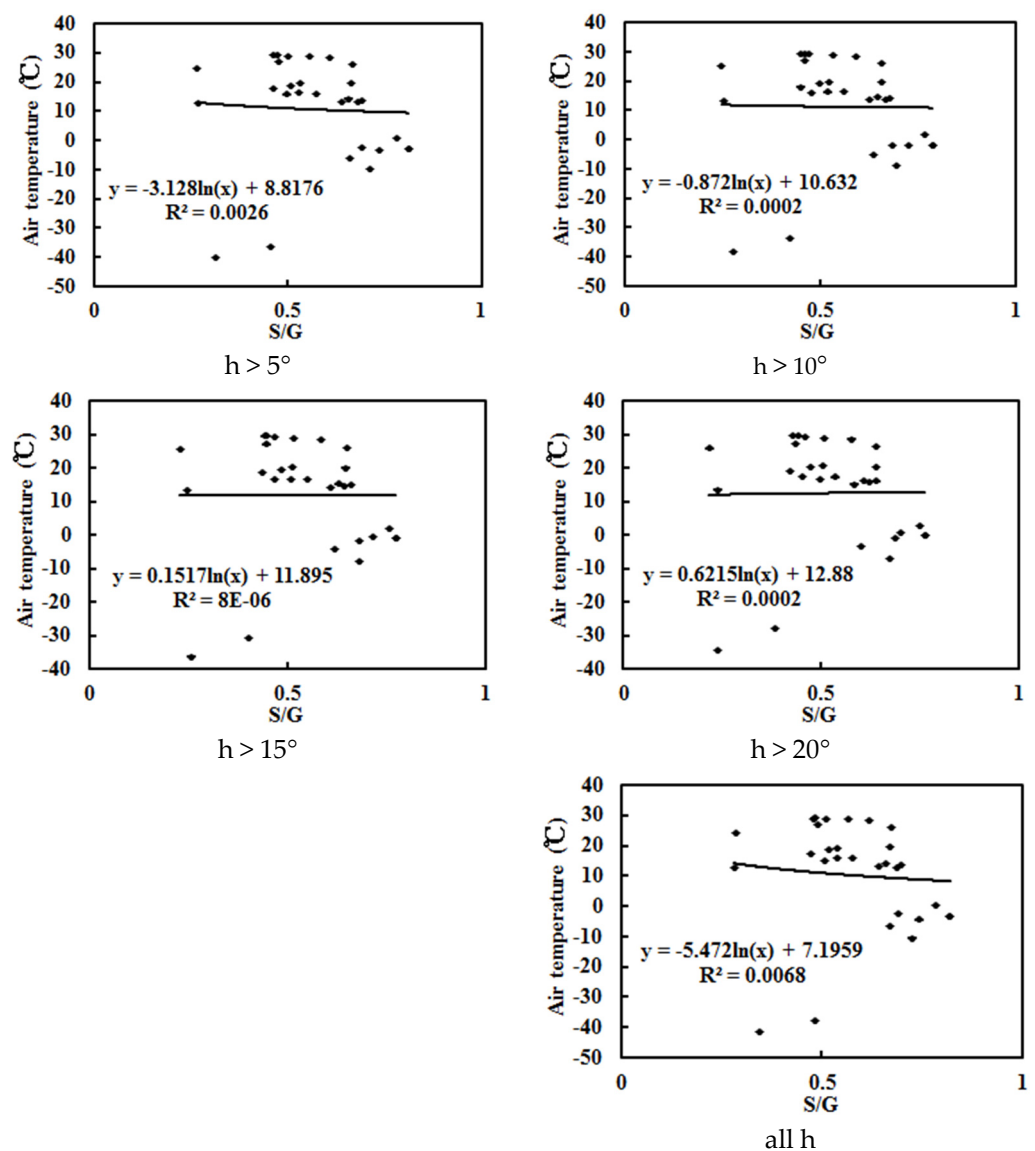


Figure 3. The relationships between annual mean T and S/G for 29 BSRN stations at different solar altitudes ($h > 5^\circ$, 10° , 15° , 20° , and all altitudes) under all sky conditions ($S/G = 0$ – 1.0).

Table 4. Same as Table 2, but for 29 BSRN stations under all sky conditions ($S/G = 0\text{--}1.0$), and number of years (NY).

Station (Abbr.)	$h > 5^\circ$	$h > 10^\circ$	$h > 15^\circ$	$h > 20^\circ$	All	NY
ALE	26,837	22,477	16,775	9701	29,096	9
BAR	54,411	43,576	34,667	26,787	58,556	18
BIL	92,444	85,903	78,087	70,720	97,495	25
BOU	66,698	60,764	55,975	49,179	70,791	18
CAB	64,379	57,834	48,700	39,847	67,255	17
CAR	83,285	76,735	68,461	59,765	88,693	22
CLH	51,734	47,863	43,806	39,279	54,562	15
CNR	47,385	43,140	39,292	34,300	49,535	12
DAR	48,643	45,307	42,505	39,344	50,663	12
DOM	40,616	31,178	23,629	17,413	46,260	15
FUA	46,925	44,104	40,244	37,192	48,485	12
GOB	40,627	37,883	34,784	31,901	43,854	10
GVN	96,807	76,637	60,922	47,050	100,000	29
ISH	47,256	44,727	41,447	37,852	48,941	12
IZA	50,369	46,252	43,113	38,556	53,973	13
KWA	40,388	37,389	34,613	33,205	41,682	17
LIN	98,076	88,264	73,008	61,264	1E+05	26
LRC	30,987	28,717	26,351	23,687	32,461	8
MAN	60,523	56,086	53,985	50,152	63,419	16
MNM	48,699	45,653	42,078	38,393	51,204	12
NAU	52,476	46,847	45,667	43,166	54,295	14
NYA	100,000	87,202	60,691	41,313	1E+05	30
PAL	61,414	56,334	48,863	40,410	64,501	19
PAY	100,000	98,768	88,449	73,483	100,000	29
PTR	17,619	16,668	15,512	14,378	18,840	7
SON	37,042	33,650	29,437	24,638	39,488	10
SPO	56,269	47,349	36,405	22,789	61,194	19
SYO	80,104	64,264	51,129	39,791	92,184	27
TAT	54,411	43,576	34,667	26,787	58,556	26

3.3. A Relationship Between T and Atmospheric Substances Under All Skies ($S/G = 0\text{--}1.0$) Using Polynomial Fitting

To thoroughly understand the complicated mechanism between T and S/G , further investigations were conducted using polynomial fitting for the relationship between T and S/G at 29 stations under all skies. The results are shown in Figure 4. The correlations between T and S/G increased with the solar altitude from 5° to 20° , and were larger than the corresponding values in Section 3.2. This reveals that there were two ways in which air temperature changed—air temperature increased with the increase in S/G when $S/G < 0.5$, and decreased with the increase in S/G when $S/G > 0.5$, indicating that atmospheric substances play the crucial and controlling roles in air temperature and its change—through the storage of solar energy in the atmosphere and through its usage:

(1) most of the solar energy were used to heat the atmosphere at low-S/G conditions, while (2) most of them were consumed by GLPs in CPRs via different ways (discussed in the above sections) and were not fully used to heat the atmosphere at high-S/G conditions. It is evident that the $S/G = 0.5$ is a turning point/balance point in controlling the relationship between T and S/G from positive to negative. Based on the above, it can be recognized that the air temperature decreases (climate cooling) at some sites and regions, due to the high atmospheric substance content (high S/G); in contrast, air temperature increases at the two polar regions because they have the low atmospheric substance contents with S/G s of 0.59 and 0.31 for the Sodankylä and Dome C stations, respectively [23]. Furthermore, it is natural and reasonable that the air temperature increases in some regions and decreases in other regions on the Earth.

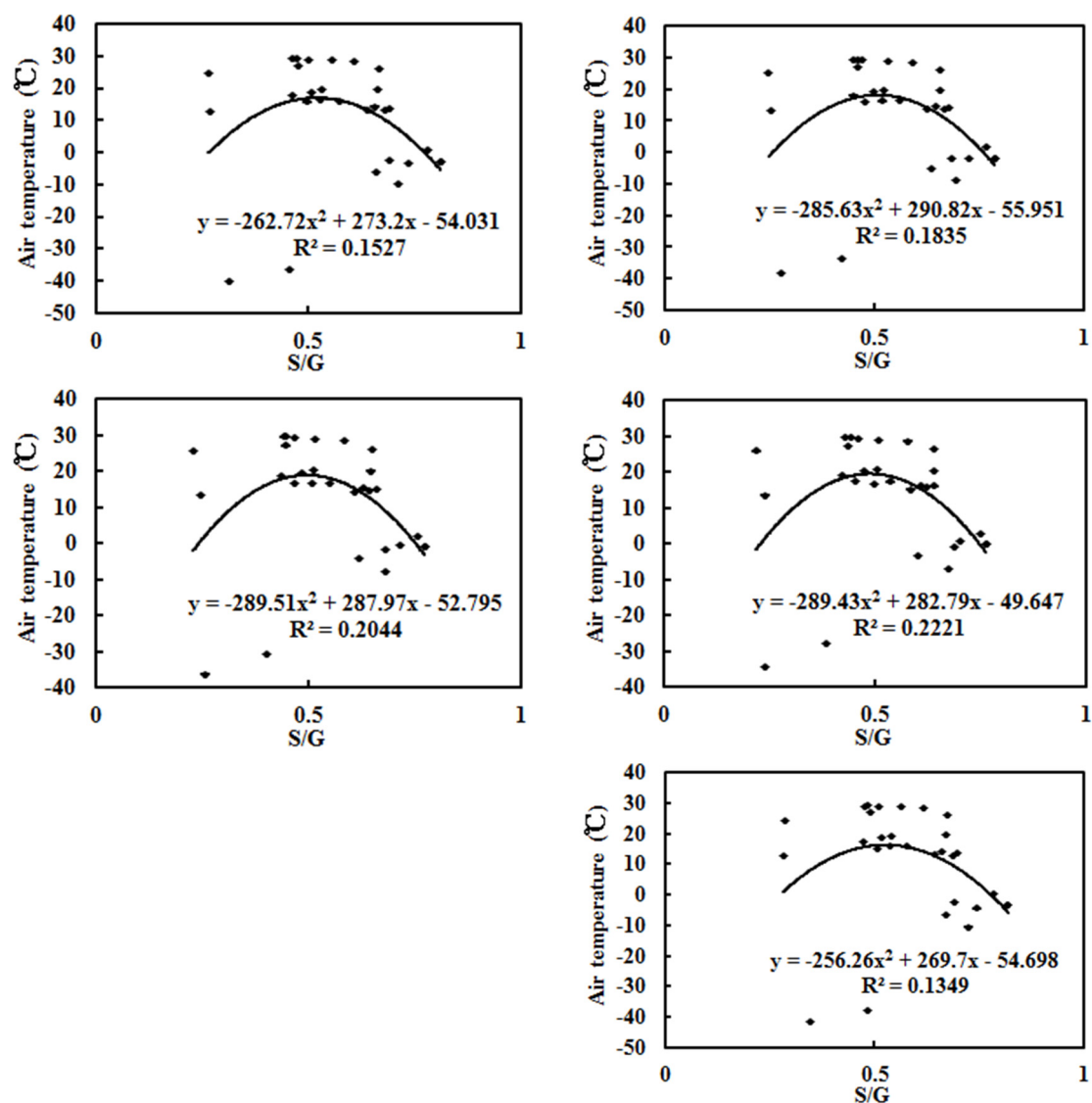


Figure 4. Same as Figure 3, but using polynomial fitting for T and S/G .

It should be noted that the relationships (equations) between T and S/G under different S/G conditions describe the mean state of the atmosphere over long time scales, and that there were fluctuations at each site.

3.4. Application of the Relationship Between T and S/G ($S/G < 0.6$, $h > 20^\circ$)

The relationship between T and S/G determined using 26 stations at $S/G < 0.6$ and $h > 20^\circ$ is described as

$$T = 85.32 \times \ln(S/G) + 125.73 \quad (R = 0.723, n = 26) \quad (1)$$

where T is the air temperature and S/G is the ratio of diffuse solar radiation to global solar radiation. This equation was applied to estimate the air temperature. The result is shown in Figure 5. The minimum T of -273.15°C (absolute zero) can be achieved when S/G decreased to 0.009327, which is in good agreement with the 0.009251 value determined using a similar equation at four typical stations (Sodankylä, Dome C, Ankara, and Qianyanzhou) [25]. The air temperature inferred using more representative BSRN stations over multiple years is also in good agreement with the absolute zero in thermodynamics. It represents very low GLP loads and a clean atmosphere, i.e., a highly idealized state on the Earth.

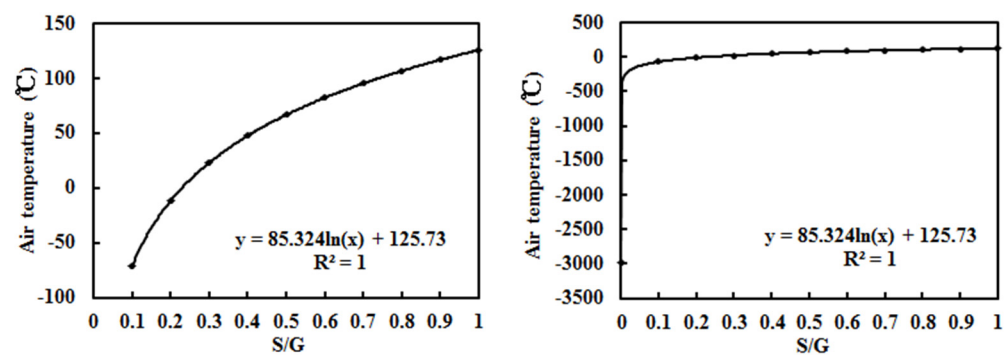


Figure 5. The calculated hourly averages of air temperature under all sky conditions using Equation (1) for two situations at $S/G = 0.1$ – 1.0 (left) and 0.0 – 1.0 (right).

Continuously applying Equation (1), the minimum air temperature can be decreased to -46136.9°C at $S/G = 1 \times e^{-542.2}$, and similar results were also obtained by our previous study at four stations [25]. They implied that there would be an extremely cold atmosphere (or cloud surface/source in the universe) at extremely low atmospheric compositions (close to zero, with no power to keep the energy inside), together with the conditions of close to no light ($S = 0$). This very strange temperature violates the present law of thermodynamics. In addition, there was no output of T at $S/G = 0$, indicating that temperature is an important parameter of the atmosphere and matter. A similar relationship to that in Equation (1) was previously obtained at four typical sites (including two polar sites) using good quality observations; e.g., the Qianyanzhou and Sodankylä stations have similar standard deviations of the observed global solar radiation as the Dome C site [24,25]. It should be mentioned that the above sites cover the northern and southern hemispheres. The relationship between T and S/G existed at most typical climate (or latitude) zones, including the Arctic and Antarctic circles, with time scales ranging from 18,840 to 113,445 h for all altitudes under all skies, corresponding to 7–30 years.

Merali (2013) [34] reports that the “Temperature in a gas can reach below absolute zero thanks to a quirk of quantum physics”, and this can be understood as an example and a primary support for the above results and speculations. More explorations and confirmations by different disciplines are necessary in the future.

It should be emphasized that this study investigated the relationships between T and S/G across multiple years under relatively idealized atmospheric states, and discovered

the mechanism behind the phenomenon. These relatively idealized atmospheric states can be considered as the idealized average states of the atmosphere at typical BSRN stations.

Based on Equation (1), it is further speculated that there are no limitations for the minimum T for the idealized atmosphere, implying that these situations may be possible somewhere in the universe. This is also based on some similarities described in the origin of the universe (e.g., the big bang) and the movements (e.g., rotation and revolution) of the nine planets in the solar system. The relationship between T and S/G expresses a link between the internal energy and GLPs in the atmosphere, and is further assumed to exist on other planets or elsewhere in the universe. This hypothesis may be considered as a reference point from which to explore the basic features of the universe in the future. The large positive and negative temperatures may reflect the true temperature, and the small mean temperature of the universe.

3.5. Mechanism Analysis of the Relationship Between T and S/G

In nature, air temperature reflects the net internal energy accumulated and stored in the atmosphere. When global solar radiation transfers into the atmosphere, it is absorbed and scattered by GLPs in the atmosphere. Part of this energy is utilized by many GLPs reacting with VOCs and O_3 through OH and NO_2^* radicals, and H_2O in the UV and visible regions [3,4,15–25], and the remaining energy can be used to warm the atmosphere. In addition, large amounts of GLPs (GHGs (CO_2 , CH_4 , N_2O , water vapor, etc.), non-GHGs (thousands of AVOCs and BVOCs, α -dicarbonyl compounds, organic aerosols from the oxidations of BVOCs, etc.) absorb and/or use UV, visible, and near-infrared radiation and warm the atmosphere [3,15–25,35–41]. More attention should be paid to numerous UV, visible, and near-infrared absorbers (NO_2 , SO_2 , O_3 , VOCs, and their oxidation products; nitrated aromatic gases; nitrated and aromatic aerosols; and fine particulate matter (BC and SOA); etc.) [42–48], along with their absorption and scattering energy. No matter how the GLPs change in the atmosphere, the available global solar energy is the dominant controlling factor in GLPs' change and their conversions between their gas, liquid, and particle phases.

An empirical model of global solar radiation (EMGSR, Equation (2)) is developed with reasonable calculations of G at the surface and at the top of the atmosphere (TOA). It can also calculate the absorbing and scattering losses or attenuations caused by atmospheric GLPs, and the reflections at the surface and the TOA [23–25,40,41]. The air temperature increase at the Dome C station in the Antarctic during 2006–2016 was mainly caused by the increases in absorbing and scattering losses, well as being associated with the increases in both S/G (representing the scattering GLPs) and water vapor pressure at the ground (representing the absorbing GLPs). This is a robust confirmation of the positive relationship between T and S/G . The important and core mechanism of T and S/G at Dome C is displayed very clearly, which is beneficial as the atmosphere at Dome C is the cleanest and driest on Earth (i.e., the lowest absorbing and scattering GLPs, reflected by E and S/G , respectively). Additionally, the aerosol optical depth (AOD) is also the lowest on Earth. Meanwhile, the air temperature also increased at the Sodankylä (in 2001–2018) [41], Qomolangma (2007–2020), and Ankara province (2017–2019) stations, and the causes of these air temperature increases are changed and different to that at Dome C due to differences in the atmospheric GLPs, the absorbing and scattering losses and their ratios to the total loss, and the reflections (or albedos) at the surface and TOA [30–50]. Therefore, a complex mechanism existed at each site but varied across sites, depending on the GLPs (both absorbing and scattering, and their relative contributions to the total GLPs), and their energy roles (and the distributions of absorption and scattering), along with the interactions between GLPs and G at the TOA, in the atmosphere, and at the surface. This is the key

reason to control the air temperature and its change. Based on the integrated results at different sites with different time scales, the basic and similar internal laws and mechanisms associated with the interactions between T and S/G were revealed without the influences of location and time period; i.e., the law represents the basic features of solar radiation and atmospheric substances and their interactions, and is thus independent of place and time.

$$G_{cal} = A_1 e^{-kWm} \times \cos(SZA) + A_2 e^{-S/G_{obs}} + A_0 \quad (2)$$

where the subscripts cal and obs express the calculated and observed hourly values of global solar exposure (MJ m^{-2}), SZA is the solar zenith angle (degree), and S is the diffuse solar radiation (MJ m^{-2}) on the horizontal plane. The first and second terms on the right side of Equation (2) describe the absorption and scattering of GLPs in the atmosphere, respectively. Coefficients A_1 and A_2 express the individual G at the TOA associating with the absorption and scattering GLPs, respectively, and A_0 expresses the reflection of G at the TOA [23–25,40,41]. Additionally, the albedos at the TOA and the surface can be calculated using the coefficients in the empirical model of G (EMGSR).

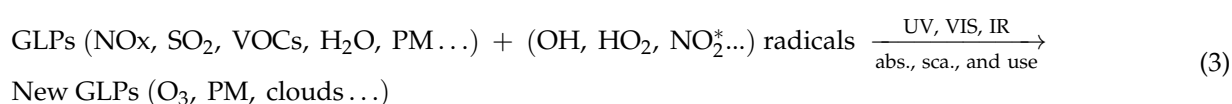
As an example for using the EMGSR, 1) the calculated absorbing loss (G_{LA}) divided by S/G and then air temperature ($G_{LA}/(S/G)/T$) is 0.23, 0.29, and $0.08 \text{ MJ m}^{-2} \text{ } ^\circ\text{C}^{-1}$ for the Dome C, Sodankylä, and Qianyanzhou sites, revealing that the atmosphere at the two polar regions has higher stored energy and heat capacity per unit of atmospheric GLPs (S/G) and T than Qianyanzhou (by about three-fold) [40]. 2) The positive correlations are 0.963 between T and $G' + G_{LA}$ and 0.903 between mean T and G' for Sodankylä, Qianyanzhou, and Dome C sites, indicating that the available G at the surface also contributes to the increase in air temperature, and the surface type and area are also important factors. Here, $G' (= G_{cal} \times (1 - \text{albedo at the surface}))$ is the absorbed global solar radiation at the ground and a potential source of heating energy as longwave radiation that warms the atmosphere.

The following important issues should be emphasized: (1) That there are many absorbers in the UV and visible regions, such as H_2O , formaldehyde [51], methyl hydroperoxide (CH_3OOH), aldehydes [52], H_2O_2 , and D_2O_2 vapors [53], nitrated aromatic gases, nitrated and aromatic aerosols and other fine particles, and VOCs and their oxidation products [18,20,21,53–57]. (2) Radicals are produced in the UV and visible regions, such as OH radicals produced from O_3 photolysis ($\text{O}_3 + h\nu (\lambda < 320 \text{ nm}) \rightarrow \text{O}(^1\text{D}) + \text{O}_2$, $\text{O}(^1\text{D}) + \text{H}_2\text{O} \rightarrow 2\text{OH}$) [15–18]; HO_2 radicals produced from HCHO photolysis [51], where excited NO_2^* reacts with water molecules [19]; and the photolysis of CH_3OOH and $\text{O}_3 \cdot \text{H}_2\text{O}$ clusters [20,58]. Almost all GLPs can react with OH and the above additional radicals, H_2O , NO_2^* , and VOCs in CPRs, and produce new types of GLPs, during which much UV and visible energy is transferred, consumed directly by absorbers and/or indirectly by using the energy from other absorbers, and/or is accumulated in the atmosphere.

In the near-infrared and/or infrared regions, there are many absorbers. Apart from the common GHGs (water vapor, CO_2 , CH_4 , and N_2O), there are AVOCs and BVOCs (e.g., bromomethyl peroxy radical (CH_2BrOO)) [42]; HFC-125 and HFC-143a [59]; HCHO, HCDO, and DCDO [60]; isoprene [61] and acetone [62]; water dimer (H_2O_2) [63]; and particles (e.g., smoke particles, organic carbon (OC), and black carbon (BC)) [64–66]. The isoprene exhibits infrared (IR) absorption [60], extending its roles from the UV and visible regions to the IR region. All of the above VOCs and their oxidized compounds with IR absorption properties made significant CPR connections between the UV, VIS, and IR regions, forming an entire CPRs system.

To summarize the above, some GLPs exhibit absorption in the UV and visible regions, the others without absorption properties can use the energy indirectly via CPRs with OH, HO_2 , NO_2^* radicals, H_2O , and the substances exhibiting absorption. Namely, almost all GLPs absorb, transfer, and utilize UV, visible, and near-infrared (NIR) energy through

different ways/mechanisms (Equation (3)). The most important thing to emphasize is that the OH and NO₂* radicals play the key roles in CPRs in a single phase of a gas, liquid, and particle, and their connections/conversions. Additionally, water vapor plays vital roles in the production of OH and NO₂* radicals, as well as in IR absorption. The absorbing loss/attenuation of global solar radiation in the atmosphere in the total loss caused by the absorbing GLPs plays a dominant role at some typical regional and global sites, such as in the three polar regions, at a medium latitude (Ankara province), a low-latitude (Qianyanzhou) site (the contributions of absorbing loss to total loss range from 62.0% at Sodankylä to 95.5% at Dome C) [23–25,40,41], and in Greece [67] (43 stations, 35.1–41.5° N), revealing that the absorbing GLPs are predominant in the total GLPs and result in dominant absorption loss in the atmosphere as a heating source in the above regions (48 stations), which is the dominant reason why we control the emissions of the main GHGs (CO₂, CH₄, N₂O, etc.). Furthermore, the scattering loss of global solar radiation plays secondary roles and also contributes to energy utilization in the atmosphere–land system. Therefore, the atmospheric compositions obey the basic law during their changes (Equation (3)).



Based on this study and other studies, air temperature increased at most sites, but also decreased at other sites. The reasons and mechanisms are clearly shown at Dome C, and changed and varied across the sites. The key factors controlling the air temperature change are absorbing and scattering GLPs and their contributions to the total GLPs, the loss of G in the atmosphere, reflections of G at the TOA and the surface, and the absorption of G by the ground. The above parameters and their changes play significant roles in the effectively internal energy of the atmosphere (EIEA, the energy that can be used to heat the atmosphere) and air temperature, and the atmospheric GLPs and solar radiation should be studied as a whole.

It should also be mentioned that there are still more unmeasured and simulated chemicals and radicals (e.g., missing simulated OH [68]), the roles of which in the atmosphere were ignored and should be fully considered in model studies (e.g., General Circulation Models (GCMs) [69] and climate change. The energy balance method (EMGSR) provides a tool to understand the dynamic energy roles and connections for all GLPs in their associated physical, chemical, and photochemical processes without considerations of the specific processes, radicals, and chemicals, especially those that remain unknown and/or unmeasured [15–21,24,25,36–39,57].

Given the radiation transfer in the atmosphere, combined with its interactions with the absorption and scattering GLPs and the ground (Figure 6, Equations (2) and (3)), it is suggested to reduce the direct emissions of all sorts of GLPs (GHGs, non-GHGs, liquids, and particles), and the secondary production of GLPs via CPRs in the atmosphere. Only in this way can a clearer atmosphere be achieved, can more carbon be stored in plants, and can regional and global climate warming be slowed down [70,71]. Finally, multiple beneficial effects and friendly and suitable environments for the nature–human system will be established in the future by the efforts of all humankind. This recommendation is further supported by using more typical and reliable BSRN station measurements over long time scales (7–30 years) than those in our previous proposed model using four stations [25]. To reduce direct GLP emissions, apart from the regular measures (more stringent emission controls of NO_x, SO₂, CO, AVOCs, PM, etc.), BVOC emissions should be taken into consideration to a greater extent—especially if an afforestation strategy will be conducted to achieve carbon neutrality in the world [70,71]—as BVOCs are highly reactive and react to OH radicals and most GLPs, and produce new GLPs (O₃, SOA, PM_{2.5}, etc.). BVOCs

also play significant bridge roles in chemical transformations along with solar energy usage (PAR and UV) among gases, liquids, and solids in the atmosphere, and between the atmosphere and the biosphere [3,15–21]. Therefore, it is suggested to take action to mitigate their emission, with the main aims being to reduce high BVOC emissions, including (1) by planting trees, grasses, and flowers using low or no isoprene and monoterpene emitters [72–74] in big cities and mega-city regions in the future; (2) by cutting the branches of trees and grasses after 16:00 in cities and gardens, and spraying and/or shading the canopies of plants if possible, considering that BVOC emissions are larger at high PAR and temperatures [1,3,73,74]; (3) by reducing biomass burning or adjusting the time period of biomass burning (with after 16:00 suggested), as high BVOC emissions along with O_3 production occur during and after burning periods [73,74]. Based on the above actions, the secondary formation of new GLPs through CPRs can be reduced effectively.

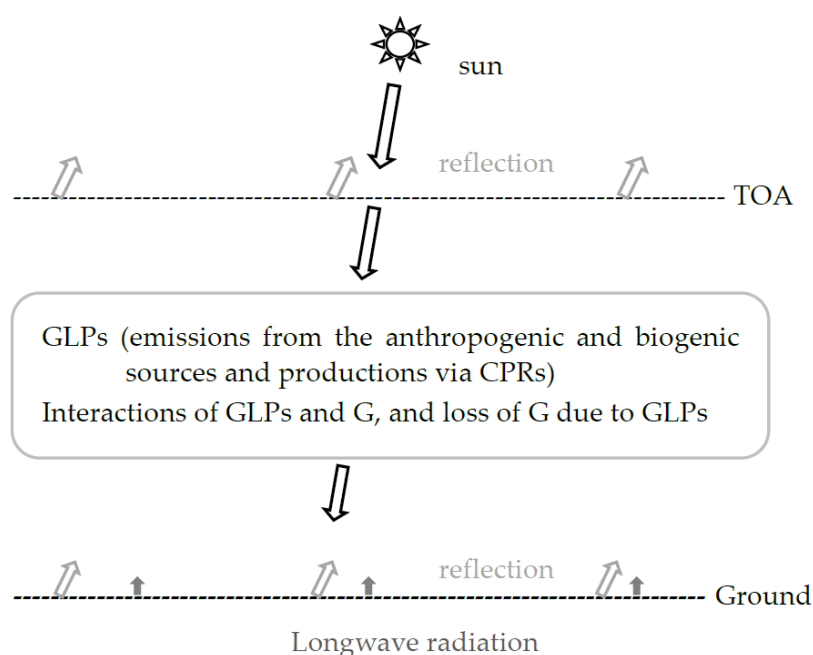


Figure 6. Global solar radiation transfers in the atmosphere, reflections at the TOA and the surface, and longwave radiation converted from the received global solar radiation.

It should be noted that (1) O_3 and SOA are important secondary GLP products, and O_3 and some SOAs are UV and VIS absorbers [3,15–21]. (2) Water vapor is a critical component and one of the important GHGs and contributes to S/G. It also plays vital roles in (a) OH and NO_2^* formation through CPRs and new GLP productions (e.g., aerosols, clouds), and (b) the absorption and scattering of solar global radiation [15–20]. Additionally, water vapor is strongly associated with air temperature and relative humidity, and water vapor and S/G are usually higher in summer than in winter [3]. (3) In the context of global warming, observations and model studies report that an increase in temperature usually together with an increase in solar radiation (UV, VIS, and NIR) affects changes in air quality, because the chemical reaction rates of reactants and new photochemical reaction products (in gas, liquid, and solid phases, e.g., O_3 , aerosols, etc.) and BVOC emissions will increase, resulting in severe air pollution, more solar radiation accumulation in the atmosphere, and less solar radiation arriving at the ground [3,15,16,23–25,73–77]. (4) The relationship of T and S/G demonstrates an intrinsic link and basic interaction between the internal energy of the atmosphere (EIEA) and atmospheric GLPs in the whole column. It contains many significant aspects: (a) matter, i.e., GLPs, including NO_x , SO_2 , CO, CO_2 , CH_4 , N_2O , AVOCs, BVOCs, H_2O , O_3 , aerosols (SOA, BC, $PM_{2.5}$, PM_{10} , and sands in sand storms),

clouds, rainfall, snow, and hail; (b) energy, including solar radiation and its transfers and stays (absorbing and scattering losses) in the atmosphere, reflections at the TOA and the surface (i.e., albedos at the TOA and the surface), as well as radiation reaching at the surface. These aspects influence solar energy exchange and balance in the sun–atmosphere–land system. The GLPs affect the albedos at the TOA and the surface through absorption and scattering processes, which are reported in typical sites [23–25,40,41]. All of above factors drive and/or influence regional and global climate and climate change via different ways, and vice versa. The multiple interactions between all kinds of GLPs and all sorts of energies occur every day, evolving with time. Tremendous quantities of GLPs exist and change in the atmosphere–land system, playing very sophisticated roles via different physical, chemical, and biological processes; some of them are understood, and the others are still to be investigated or remain unknown [3,15,17,68]. Energy estimations that GLPs utilized/associated with give us a better opportunity to understand their roles effectively without attention being paid to each chemical component and their concentration in measurements and simulations. Their energy roles can be split into absorption, scattering, and reflection, and can be studied from the TOA to the ground as one whole. Therefore, this energy-based method is another way to fully study the sun–GLPs–surface (including land and oceans) system [23–25,40,41]. Thus, extensive observations and solar radiation transfer and balance investigations of the interactions between GLPs and the oceans are an urgent necessary, and should be thoroughly studied, as the oceans occupy about 70% of the Earth’s surface.

On the basis of the above discussions, it is feasible and effective to develop and apply EMGSR to thoroughly study global solar radiation and its interactions with GLPs, as well as the reflections at the surface and TOA, together with climate change in the interested regions.

To clearly discover the internal law of nature, it is suggested to select and use relatively clear atmospheric conditions (such as $S/G < 0.5$ or 0.6) for the analysis. Under these conditions, the internal law of nature was less affected by the influence of high GLP loads together with low solar radiation and its larger observational errors.

4. Discussions

Phenomena of Air Temperature Change at More Sites Under All Sky Conditions

The change rates of air temperature (during day time, same as in the above text), global solar radiation, and S/G , as well as mean S/G , at 29 stations are given in Table 5.

The air temperature increased at 21 stations, corresponding to the increases in G and S/G (station number $SN = 7$), the increases in G and decrease in S/G ($SN = 12$), the decrease in G and increase in S/G ($SN = 1$), and the decreases in G and S/G ($SN = 1$). The S/G ranged from 0.28 to 0.82, with an average of 0.60 for 21 stations. The air temperature decreased at eight stations, corresponding to the decreases in G and S/G ($SN = 3$) and the relatively high S/G , generally above 0.5, the decrease in G and increase in S/G ($SN = 3$), and the increases in G and S/G ($SN = 2$). There was a very complicated relationship between the air temperature changes and G and S/G , and it was not easy to find a clear correlation, implying that air temperature and its change was not influenced/controlled by some key factors/parameters, but by the energy (i.e., absorbed and scattered global solar radiation) that heats the atmosphere [23–25,40,41]. Though most BSRN stations showed air temperature increases with a ratio of 72.4% in all BSRN stations ($n = 29$), there were some other stations (with a ratio of 27.6%) that displayed decreases in air temperature, indicating that both increases and decreases in air temperature happened in the natural environment. Generally, there were evident relationships between air temperature increases and S/G levels for 21 stations, as well as between air temperature drops and S/G levels for 8 stations,

indicating that S/G level is not the only factor influencing air temperature change. There were no clear spatial patterns in air temperature change related to latitude, altitude, and surface type. Meanwhile, energy (lost in the atmosphere, including through absorbing and scattering, and longwave radiation emitted from the ground) is the main and key driving factor warming the atmosphere. This is confirmed by some studies at typical sites on the Earth [23–25,40,41]. The above-mentioned energy plays different roles associated with absorbing and scattering GLPs and their changes, and is site-dependent.

Table 5. The change rates of air temperature, global solar radiation, and S/G per year ($^{\circ}\text{C}/\text{year}$, $\text{W m}^{-2}/\text{year}$, unitless), together with mean S/G, at 29 BSRN stations.

Station (Abbr.)	T	G	S/G	Mean S/G
ALE	−0.2332	−0.4839	−0.0081	0.73
BAR	0.0032	1.3839	−0.0005	0.82
BIL	0.0179	0.1726	−0.0009	0.52
BOU	−0.0836	0.2169	0.0032	0.51
CAB	0.0492	1.4756	−0.0036	0.70
CAR	−0.0279	0.1826	6E−05	0.47
CLH	0.0564	1.821	0.0011	0.54
CNR	0.0493	0.5838	0.0007	0.58
DAR	−0.0044	−0.2085	0.0017	0.48
DOM	0.005	0.7969	−0.0008	0.45
FUA	0.0889	2.6255	−0.0058	0.67
GOB	0.0697	−0.7316	-3×10^{-14}	0.29
GVN	0.0068	0.1383	0.0011	0.73
ISH	0.066	1.1379	−0.003	0.67
IZA	0.0249	−1.0228	−0.0008	0.28
KWA	−0.0092	−3.1484	−0.0031	0.53
LIN	0.0786	0.8227	−0.0024	0.69
LRC	0.0777	0.8246	−0.0014	0.54
MAN	−0.0077	−1.614	0.0023	0.62
MNM	0.1083	0.7437	0.1083	0.49
NAU	−0.0413	−0.7612	−0.0413	0.51
NYA	0.0516	0.1928	0.0011	0.79
PAL	0.0473	6.8274	−0.0242	0.73
PAY	0.0714	1.2654	−0.0013	0.64
PTR	0.0193	−1.0556	0.0027	0.49
SON	0.0361	0.2437	−0.0062	0.69
SPO	−0.0257	−1.5954	0.0043	0.48
SYO	0.0197	0.6473	0.0007	0.67
TAT	0.0152	0.6856	−0.0018	0.65

Numerous studies have reported that air temperature has increased at a total of 186 stations in China (see Table 6 in reference [25]). Combined with the above observations, air temperature increased at most sites, and also decreased at other sites. Therefore, air

temperature change or climate change is a challenging task to fully investigate, and more specific research is needed at every site or region.

We should also pay attention to the geographical and astronomical factors, along with the atmospheric factors affecting solar radiation, and their roles in climate change (e.g., climate warming and/or cooling) [25].

In view of the better development of the economies of all countries, healthy atmospheric environments (i.e., a clean atmosphere) and a suitable climate (i.e., slowing down climate warming), we should consider a balanced way to adjust the above issues and make effective policies.

According to the relationships between T and S/G under different conditions of S/G (<0.5 , <0.6 , and all) in Sections 3.1–3.3, we also should consider a suitable extent to which to reduce climate warming, so as to avoid an adverse and extreme event in terms of reducing S/G , because air temperature will be gradually decrease with the decrease in atmospheric substances (anthropogenic emissions and secondary production associated with the development of the economy) at $S/G < 0.5$, $S/G < 0.6$, and at other values. There are control points for the warming range to be a suitable temperature range for human beings; a relatively low temperature range or very low temperature ranges are not suitable for human life, depending on the locations with special GLPs (e.g., Figures 1–4). There are also constraints when using Equation (1) with $S/G < 0.6$ and others under different situations (h and S/G). The $S/G = 0$ is an idealized hypothesis for further exploration of the possibility for a minimum air temperature. There are balances to be struck concerning mitigating climate warming or cooling (site, GLPs, and associated energy dependence), economic and social development, and suitable environments for human beings, animals, and plants, etc. The controllable range will depend on the efforts of the government, all industries, scientific research, and so forth.

One important issue should be emphasized: that a change or a large change in global solar radiation should be considered in climate studies and climate change, because it will lead to the changes in global solar radiation in the atmosphere, at the TOA and the surface over all regions globally, along with atmospheric substances and their internal relationships, i.e., the Earth system. These influencing factors include solar activity, solar constants, the orbit of the Earth and its axial inclination, the Earth's angular rotation [78,79], etc.

5. Conclusions

On the basis of analyzing the reliable global solar radiation and meteorological variables over long time scales (7 to 30 years with hourly continuous measurements) at 29 BSRN stations on the Earth, a strong non-linear positive relationship between air temperature and atmospheric substances (i.e., T and S/G) existed extensively, which further confirmed the similar relationship previously found at four typical stations on the Earth, revealing that the atmospheric substances (GLPs) keep and accumulate internal energy in the atmosphere via the absorption and scattering of global solar radiation, and absorb longwave radiation from the ground under all sky conditions. Solar radiation interacts with atmospheric compositions, resulting in the different uses and distributions of solar energy in the atmosphere. Most of the above energy is used to heat the atmosphere and leads to regional and global climate warming. The mechanism of the relationship between T and S/G was obtained by analyzing the global and diffuse solar radiation and meteorological variables under relatively idealized atmospheric conditions (i.e., $S/G < 0.5$ and 0.6). The reliable and long time scale solar radiation and meteorology data, selected from 29 BSRN stations from across the whole Earth, reflect the changes in and the interactions among solar radiation, atmosphere, GLPs, climate change, and the orbit of the Earth in an integrated manner. The method of using an idealized atmospheric state along with corresponding measurements is

a better way to deeply investigate the physical and chemical laws in the real atmosphere. Therefore, it is recommended for all humankind and all nations to reduce GLPs from all kinds of sources, including direct emissions from anthropogenic and biogenic emissions, and indirect formations of new GLPs via CPRs. GLPs include all the GHGs (CO₂, CH₄, N₂O, etc.), non-GHGs (AVOCs, BVOCs, etc.), and liquids and particles, because some of them are absorbers in the UV, visible, and infrared regions, and the others indirectly use UV, visible, and infrared radiation when reacting with the UV, VIS, and IR absorbers. In the sun–atmosphere–land system, global solar radiation is absorbed, scattered, transferred, and utilized by all GLPs through different processes and mechanisms. There are two ways in which air temperature changes under natural atmospheric conditions, positive and negative, due to different mechanisms. Air temperature increases were common at most BSRN sites and also at many sites in China. In the meantime, there were some other BSRN stations that showed air temperature decreases. These differences imply very complex mechanisms in air temperature change, depending on the key controlling factors, atmospheric substances (absorbing and scattering, and their relative ratio), the total loss of G in the atmosphere (including the losses of absorption and scattering and their distributions in the total loss), reflections at the TOA and the surface, available longwave radiation, land type and structure, etc. In other words, air temperature change reflects the changes in the internal energy of the atmosphere, and depends on the region. Most current studies focus only on the warming effects of several key GHGs and/or absorbing aerosols (black carbon, SOA, etc.), but this is one aspect of the warming effects caused by absorbing GLPs, and is incomplete in terms of global warming and climate change studies. All kinds of GLPs and their associated energy roles in the atmosphere, as well as in the sun–atmosphere–land system, should be comprehensively studied. More specific studies are still needed for the selected sites and regions of the Earth. Through the continuous efforts of the people and nations, climate warming should be reduced, and a clearer atmospheric environment and better health for human beings should also be achieved. In the future, we should create a friendly and harmonious environment for the people and nature.

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