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Solar Cycle and Anthropogenic Forcing of Surface-Air Temperature at Armagh Observatory, Northern Ireland

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LIST OF SYMBOLS AND ABBREVIATIONS

10-yma	10-year moving average
Aa	Aa geomagnetic index
AGGI	Annual Greenhouse Gas Index
ASAT	Armagh surface-air temperature
B1	bivariate fit 1
CH_4	methane
CO_2	carbon dioxide
EN	El Niño
ENSO	El Niño Southern Oscillation
HadSST1	Hadley sea surface temperature dataset from the Hadley Center
LN	La Niña
MLCO2	Mauna Loa carbon dioxide
N3.4	Niño 3.4 region
NO_2	nitrous oxide
P1	contribution of the Annual Greenhouse Gas Index of carbon dioxide
P2	contribution of the Annual Greenhouse Gas Index of carbon dioxide plus methane
P3	contribution of the Annual Greenhouse Gas Index of carbon dioxide plus methane plus nitrous oxide
SSN	sunspot number
T	trivariate
VEI	volcanic explosivity index
y_1	regression equation 1
y_2	regression equation 2

NOMENCLATURE

r	coefficient of correlation
sd	standard deviation
se	standard error of estimate
t	year

TECHNICAL PUBLICATION

SOLAR CYCLE AND ANTHROPOGENIC FORCING OF SURFACE-AIR TEMPERATURE AT ARMAGH OBSERVATORY, NORTHERN IRELAND

1. INTRODUCTION

The Armagh Observatory temperature record is one of the longest, continuous, thermometer-based temperature records available for study.[1–8] Mean monthly and annual temperatures, based on daily temperature readings using minimum and maximum thermometers, extend continuously from 1844 to the present, now spanning 165 yr.

The Armagh Observatory lies about 1 km northeast of the center of the ancient city of Armagh, Northern Ireland,[6] being located at latitude 54°21′12″ N. and longitude 6°38′54″ W. and situated about 64 m above mean sea level at the top of a small hill in an estate of natural woodland and parkland that measures about 7 ha. Previous studies[5] have shown that its rural environment has ensured that the Armagh Observatory suffers little or no urban microclimatic effects and that its temperatures can be used as a good proxy for monitoring long-term trends in both northern hemispheric and global annual mean temperature.[4]

This study reexamines the extended record of Armagh Observatory annual mean temperature, in particular, as related to the solar cycle (i.e., sunspot number (SSN) and the Aa geomagnetic index (Aa)), the annual mean temperature of the Niño 3.4 region (N3.4) (5° N.–5° S., 120–170° W.), and the annual mean Mauna Loa carbon dioxide (CO_2) (MLCO2) measurements. While 10-yr moving averages (10-yma) of Armagh Observatory annual mean temperatures correlate quite strongly with solar cycle indices, especially over the first 130 yr or so, this correlated behavior has become much less apparent since about 1980. Instead, the correlation over the past 30 yr or so appears better related to rising levels of atmospheric CO_2. In fact, for the common interval 1963–2003, a bivariate fit using Aa and MLCO2 values is found to describe the 10-yma of the Armagh Observatory surface-air temperature very closely, having a coefficient of correlation $(r) = 0.948$ and standard error of estimate $(se) = 0.11$ °C, and a trivariate fit employing Aa, MLCO2, and SSN is slightly stronger, having $r = 0.952$ and $se = 0.1$ °C.

2. RESULTS AND DISCUSSION

Figure 1 displays 10-yma values of (a) the annual mean surface-air temperature at Armagh Observatory (ASAT) for the interval 1849–2003 in °C, (b) the annual mean SSN for the interval 1849–2003, (c) the annual mean Aa for the interval 1873–2003 in nT, (d) the annual mean sea-surface temperature in the N3.4 for the interval 1876–2003 in °C, and (e) the annual mean value of the MLCO2 atmospheric concentration for the interval of 1963–2003 in ppmv. The thin horizontal lines represent the parametric means over the individual lengths of observation. The standard deviation (*sd*) for each parameter is also given. Hence, the average 10-yma value (±1 *sd*) of ASAT = 9.20 ± 0.33 °C, SSN = 56.4 ± 18.2, Aa = 21.4 ± 3.5 nT, N3.4 = 26.97 ± 0.15 °C, and MLCO2 = 344.18 ± 17.17 ppmv. Coefficients of correlation and the inferred regression equations (y_1 and y_2) are likewise given in each subpanel, comparing ASAT against the other parameters. Thus, of the two solar cycle parameters, SSN and Aa, the correlation between ASAT and Aa appears to be the stronger, having $r = 0.686$ over the interval 1873–2003. Limiting the fit to only those values prior to about 1980, however, one finds the correlation to be even stronger, having $r = 0.762$ (inferring that nearly 60% of the variance in ASAT can be simply explained by the variation in Aa alone), with ASAT = 7.807 + 0.063Aa. Obviously, the overall correlation between ASAT and Aa (i.e., the solar cycle) has greatly weakened since about 1980, with Aa values declining yet ASAT values rising, in contrast to the inferred correlative behavior prior to 1980. The correlation between ASAT and N3.4 is very weak, having $r = 0.268$ (inferring that <10% of the variance in ASAT can be attributed to the variation in N3.4 alone). The correlation of ASAT against MLCO2 is by far the strongest single-variate fit, having $r = 0.877$ (inferring that more than 75% of the variance in ASAT can be explained by the variation in MLCO2 alone), although the fit only spans about 41 yr.

The lowest 10-yma value of ASAT occurred in 1883, measuring 8.44 °C, and the highest value occurred in 2002 and 2003, measuring 10.13 °C. Continued warming is troubling, especially if it continues unabated, since it would certainly mean the extinction of many life forms on planet Earth and radical changes to human lifestyle.[9,10] A mere change of 2 °C could spell disaster for many communities, with changes of more than 2 °C resulting in even more ecological damage.[11]

While the record of temperature variation at Armagh Observatory can be described as episodic in nature, an undeniable rise of 1.69 °C has occurred there over the past 120 yr. The current 10-yma value (10.13 °C) is now 0.93 °C above its long-term mean. A linear fit (y_1) of ASAT with time for the interval 1883–2003 yields the regression ASAT = –5.251 + 0.00746*t*, where *t* is the year, $r = 0.792$, and $se = 0.08$ °C. Presuming a continued unabated rise, one would expect the 10-yma of ASAT to be about 2 °C above its long-term mean within about 200 yr. However, because the rise has been much steeper since 1982, it could attain 11.2 °C much sooner, in as short as about 21 yr (calculated from the 2003 last available entry) or in the year 2024, based on the inferred regression (y_2) ASAT = –91.185 + 0.05059*t*, where $r = 0.989$ and $se = 0.26$ °C.

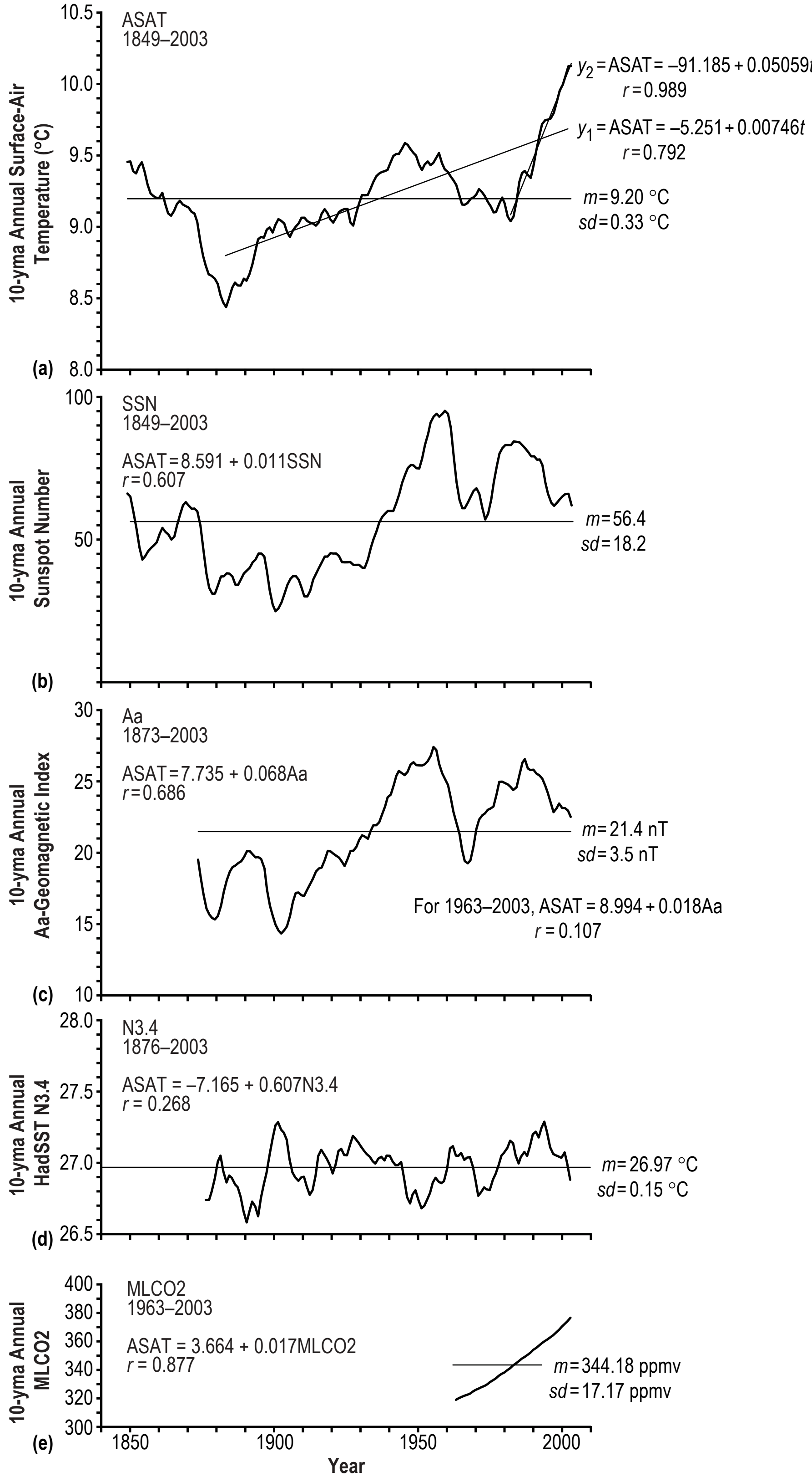

Figure 1. Temporal variation of 10-yma values of (a) ASAT, (b) SSN, (c) Aa, (d) HadSST1 N3.4 region sea-surface temperature, and (e) MLCO2 for selected intervals of time between 1849 and 2003.

Further examination of figure 1 suggests close behavior between ASAT and the solar cycle, in particular, Aa. The Aa correlates with SSN, but is slightly out of phase with respect to SSN (i.e., the minimum and maximum values tend to lag that of SSN). Previous studies indicate that Aa is directly related to the solar wind speed,[12–14] so that higher values of Aa indicate faster solar wind speeds and lower values of Aa indicate slower solar wind speeds. Visually, the trend in the 10-yma values of ASAT and Aa are remarkably similar, especially, prior to about 1980 (as previously indicated above). Presuming that Aa alone can account for the observed behavior of ASAT, to obtain a 10-yma of ASAT of 11.2 °C means that the 10-yma of Aa would have to measure about 51 nT, or nearly double the highest Aa previously seen (27.4 nT in 1955, associated with the largest sunspot cycle in the modern record, cycle 19). However, the recent behavior of Aa with respect to ASAT suggests that something has changed in the relationship between ASAT and Aa, for their behaviors are now in opposition (at least, for the interval 1980–2003). (For the sake of completeness, a 10-yma of ASAT of 11.2 °C means a 10-yma of SSN of about 237, more than twice as large as has ever been seen.)

Obviously, the solar cycle alone cannot account for the observed behavior of ASAT, especially its recent behavior over the past 30 yr or so. Some other effect must be driving the rise in ASAT values. That effect appears to be anthropogenic forcing with CO_2 being the major contributor, accounting for more than 60% of the greenhouse gas concentration.[15,16]

Concerning MLCO2, its 10-yma has increased from 318.99 ppmv in 1963 to 375.60 ppmv in 2003, an increase of 56.61 ppmv (i.e., about 18% increase) over about 40 yr. To attain a 10-yma of ASAT = 11.2 °C, MLCO2 would have to measure about 443 ppmv, some 68 units higher than that measured in 2003. The values for the interval spanning 1963–2003 are consistent with an exponential fit, with values given approximately as $\log(\mathrm{MLCO2}) = -0.971 + 0.00177t$, where t is the year, based specifically on the 1963 and 2003 MLCO2 values. Extrapolating the fit forward, one finds that the value of MLCO2 = 443 ppmv would be reached about the year 2044, or in about 40 yr (from 2003). However, extrapolating the fit backwards to preindustrial times[17] (e.g., about 1880) yields values of MLCO2 that are too low when compared to the generally recognized level of atmospheric CO_2 concentration during the preindustrial era (about 230 ppmv, as compared to an accepted level of about 280 ppmv), so atmospheric CO_2 levels must have increased significantly in the recent past to account for the discrepancy. A value of about 280 ppmv would have been seen about 1930, based on an extrapolation of the exponential fit. The reader is reminded that the Mauna Loa atmospheric CO_2 measurements are the longest continuous record of atmospheric CO_2 concentrations available. The site is in a barren lava field of an active volcano located at latitude 19°32′ N. and longitude 155°35′ W. and 3,397 m above mean sea level and does not suffer local influences of vegetation or human activity. Consequently, it is considered a very favorable site for a reliable indication of trends in atmospheric CO_2 concentrations.[18,19]

Table 1 provides the annual means and 10-yma values for parameters as plotted in figure 1. The relative percentages of anthropogenic gases for the interval 1979–2008 are also included, where contributions to the Annual Greenhouse Gas Index (AGGI) are P1 (represents the contribution of CO_2), P2 (the combined contributions of CO_2 and methane (CH_4)), and P3 (the combined contributions of CO_2, CH_4, and nitrous oxide (N_2O)).

Table 1. Annual and 10-yma values of ASAT, SSN, Aa, N3.4, and MLCO2, and selected percentages.

Year	ASAT	10-yma	SSN	10-yma	Aa	10-yma	N3.4	10-yma	MLCO2	10-yma	P1	P2	P3
1844	9.20	–	15.0	–	–	–	–	–	–	–	–	–	–
1845	9.02	–	40.1	–	–	–	–	–	–	–	–	–	–
1846	10.40	–	61.5	–	–	–	–	–	–	–	–	–	–
1847	9.63	–	98.5	–	–	–	–	–	–	–	–	–	–
1848	9.19	–	124.7M	–	–	–	–	–	–	–	–	–	–
1849	9.42	9.46	96.3	66.3	–	–	–	–	–	–	–	–	–
1850	9.71	9.46	66.6	64.9	–	–	–	–	–	–	–	–	–
1851	9.55	9.39	64.5	60.4	–	–	–	–	–	–	–	–	–
1852	9.62	9.38	54.1	53.7	–	–	–	–	–	–	–	–	–
1853	8.74	9.43	39.0	46.5	–	–	–	–	–	–	–	–	–
1854	9.43	9.46	20.6	42.8	–	–	–	–	–	–	–	–	–
1855	8.71	9.39	6.7	44.2	–	–	–	–	–	–	–	–	–
1856	9.45	9.30	4.3m	46.3	–	–	–	–	–	–	–	–	–
1857	10.25	9.24	22.7	47.2	–	–	–	–	–	–	–	–	–
1858	9.58	9.22	54.8	47.7	–	–	–	–	–	–	–	–	–
1859	9.68	9.21	93.8	49.2	–	–	–	–	–	–	–	–	–
1860	8.07	9.22	95.8M	51.7	–	–	–	–	–	–	–	–	–
1861	9.31	9.24	77.2	53.5	–	–	–	–	–	–	–	–	–
1862	8.77	9.16	59.1	53.4	–	–	–	–	–	–	–	–	–
1863	9.22	9.10	44.0	51.7	–	–	–	–	–	–	–	–	–
1864	8.69	9.09	47.0	49.9	–	–	–	–	–	–	–	–	–
1865	9.63	9.12	30.5	51.0	–	–	–	–	–	–	–	–	–
1866	9.02	9.17	16.3	54.9	–	–	–	–	–	–	–	–	–
1867	8.94	9.18	7.3m	58.7	–	–	–	–	–	–	–	–	–
1868	9.79	9.16	37.6	62.0	21.2	–	–	–	–	–	–	–	–
1869	9.29	9.15	74.0	63.0	23.9	–	–	–	–	–	–	–	–
1870	9.05	9.14	139.0M	62.2	25.2	–	–	–	–	–	–	–	–
1871	9.33	9.11	111.2	61.2	24.4	–	26.61	–	–	–	–	–	–
1872	8.95	9.10	101.6	61.2	26.7M	–	26.35	–	–	–	–	–	–
1873	8.64	9.04	66.2	59.8	23.2	19.5	26.37	–	–	–	–	–	–
1874	9.03	8.90	44.7	54.7	17.6	18.3	25.99	–	–	–	–	–	–
1875	9.13	8.80	17.0	45.9	14.2	17.1	26.29	–	–	–	–	–	–
1876	8.97	8.73	11.3	37.8	12.5	16.1	26.56	26.74	–	–	–	–	–
1877	8.65	8.67	12.4	32.8	11.9	15.7	28.30	26.74	–	–	–	–	–
1878	8.87	8.65	3.4m	30.6	10.2	15.5	27.62	26.80	–	–	–	–	–
1879	7.40	8.64	6.0	31.4	10.0m	15.4	26.38	26.89	–	–	–	–	–
1880	8.93	8.60	32.3	34.1	14.5	15.6	26.69	27.01	–	–	–	–	–
1881	8.11	8.52	54.3	36.6	16.6	16.3	27.02	27.05	–	–	–	–	–
1882	8.90	8.47	59.7	37.3	26.0M	17.3	26.60	26.94	–	–	–	–	–
1883	8.46	8.44	63.7M	37.5	20.6	18.1	26.80	26.87	–	–	–	–	–
1884	9.01	8.50	63.5	37.7	17.1	18.7	27.23	26.91	–	–	–	–	–
1885	8.27	8.58	52.2	36.5	18.4	19.0	27.44	26.89	–	–	–	–	–

Table 1. Annual and 10-yma values of ASAT, SSN, Aa, N3.4, and MLCO2, and selected percentages (continued).

Year	ASAT	10-yma	SSN	10-yma	Aa	10-yma	N3.4	10-yma	MLCO2	10-yma	P1	P2	P3
1886	8.19	8.61	25.4	34.3	23.6M*	19.1	26.29	26.85	–	–	–	–	–
1887	8.56	8.59	13.1	34.0	19.4	19.3	26.46	26.83	–	–	–	–	–
1888	8.33	8.59	6.8	35.7	18.4	19.4	27.88	26.76	–	–	–	–	–
1889	9.02	8.64	6.3m	37.5	15.5	19.7	26.97	26.66	–	–	–	–	–
1890	8.99	8.63	7.1	38.9	13.7m	20.1	25.78	26.59	–	–	–	–	–
1891	8.59	8.67	35.6	40.3	20.0	20.1	27.06	26.66	–	–	–	–	–
1892	7.96	8.74	73.0	41.7	27.2M	19.9	26.23	26.73	–	–	–	–	–
1893	9.55	8.83	85.1M	43.4	20.0	19.7	25.81	26.70	–	–	–	–	–
1894	8.82	8.92	78.0	44.7	23.8M*	19.7	26.14	26.64	–	–	–	–	–
1895	8.25	8.93	64.0	45.1	21.1	19.6	27.04	26.76	–	–	–	–	–
1896	9.11	8.93	41.8	43.6	20.9	18.9	27.63	26.85	–	–	–	–	–
1897	9.00	8.99	26.2	38.5	16.6	17.4	27.13	26.93	–	–	–	–	–
1898	9.64	9.00	26.7	32.1	18.1*	16.3	26.50	27.07	–	–	–	–	–
1899	9.56	8.97	12.1	27.2	16.1	15.6	27.27	27.18	–	–	–	–	–
1900	8.61	9.02	9.5	25.4	10.5	15.0	27.80	27.27	–	–	–	–	–
1901	8.97	9.06	2.7m	26.0	9.0m	14.6	26.94	27.28	–	–	–	–	–
1902	8.76	9.05	5.0	28.4	9.5	14.4	27.80	27.23	–	–	–	–	–
1903	8.92	9.03	24.4	31.3	14.9	14.6	27.06	27.21	–	–	–	–	–
1904	8.90	8.97	42.0	33.9	14.6	14.9	27.05	27.16	–	–	–	–	–
1905	9.15	8.94	63.5M	36.0	18.0	15.6	27.95	27.02	–	–	–	–	–
1906	9.10	8.98	53.8	36.6	15.5	16.6	27.03	26.93	–	–	–	–	–
1907	8.75	9.01	62.0	36.7	19.1	17.2	26.69	26.90	–	–	–	–	–
1908	9.49	9.03	48.5	35.5	20.1	17.2	26.55	26.88	–	–	–	–	–
1909	8.50	9.07	43.9	32.7	20.1	17.0	26.19	26.90	–	–	–	–	–
1910	9.04	9.07	18.6	30.3	20.5M	17.0	26.13	26.90	–	–	–	–	–
1911	9.42	9.05	5.7	29.6	18.9	17.4	26.81	26.83	–	–	–	–	–
1912	8.84	9.04	3.6	31.9	11.8	17.8	27.28	26.78	–	–	–	–	–
1913	9.23	9.03	1.4m	35.6	11.6m	18.2	27.10	26.81	–	–	–	–	–
1914	9.46	9.02	9.6	38.2	13.9	18.7	27.56	26.91	–	–	–	–	–
1915	8.63	9.04	47.4	40.1	18.6	18.9	27.42	27.05	–	–	–	–	–
1916	9.13	9.10	57.1	42.1	22.8	19.0	26.13	27.09	–	–	–	–	–
1917	8.63	9.13	103.9M	43.6	21.2	19.5	26.64	27.06	–	–	–	–	–
1918	9.29	9.10	80.6	44.4	24.5	20.1	27.14	27.03	–	–	–	–	–
1919	8.55	9.06	63.6	44.9	25.4M	20.1	27.67	26.98	–	–	–	–	–
1920	9.42	9.04	37.6	45.1	20.5	19.9	27.28	26.93	–	–	–	–	–
1921	10.27	9.07	26.1	45.3	19.5	19.8	26.61	26.99	–	–	–	–	–
1922	8.56	9.11	14.2	43.9	21.7*	19.7	26.73	27.08	–	–	–	–	–
1923	8.89	9.12	5.8m	42.0	13.2	19.4	27.09	27.09	–	–	–	–	–
1924	8.95	9.13	16.7	42.0	13.1m	19.1	26.66	27.06	–	–	–	–	–
1925	8.88	9.13	44.3	41.9	16.0	19.5	27.25	27.06	–	–	–	–	–
1926	9.43	9.04	63.9	41.6	22.9	20.1	27.58	27.13	–	–	–	–	–

Table 1. Annual and 10-yma values of ASAT, SSN, Aa, N3.4, and MLCO2, and selected percentages (continued).

Year	ASAT	10-yma	SSN	10-yma	Aa	10-yma	N3.4	10-yma	MLCO2	10-yma	P1	P2	P3
1927	8.99	9.02	69.0	41.2	19.5	20.1	26.99	27.19	–	–	–	–	–
1928	9.20	9.10	77.8M	41.0	20.6	20.4	27.00	27.17	–	–	–	–	–
1929	8.95	9.17	64.9	40.6	22.4	20.9	27.15	27.14	–	–	–	–	–
1930	8.90	9.23	35.7	39.8	31.5M	21.2	27.78	27.11	–	–	–	–	–
1931	9.05	9.23	21.2	40.2	19.7	21.1	27.51	27.08	–	–	–	–	–
1932	9.29	9.23	11.1	43.3	22.0*	21.0	27.06	27.06	–	–	–	–	–
1933	9.73	9.27	5.7m	47.1	19.3	21.5	26.44	27.04	–	–	–	–	–
1934	9.65	9.32	8.7	49.9	16.3m	21.9	26.57	27.01	–	–	–	–	–
1935	9.29	9.36	36.1	52.7	18.6	21.9	26.89	27.00	–	–	–	–	–
1936	9.15	9.38	79.7	55.6	19.2	22.0	27.17	27.03	–	–	–	–	–
1937	9.20	9.39	114.4M	57.9	22.0	22.6	27.07	27.04	–	–	–	–	–
1938	9.75	9.39	109.6	59.4	26.5	23.2	26.60	27.02	–	–	–	–	–
1939	9.41	9.40	88.8	60.0	26.1	23.9	26.87	27.05	–	–	–	–	–
1940	9.25	9.45	67.8	59.9	26.5	24.1	27.80	27.05	–	–	–	–	–
1941	9.17	9.50	47.5	60.4	27.9	24.7	28.17	27.01	–	–	–	–	–
1942	9.25	9.51	30.6	62.9	24.7	25.4	26.61	26.98	–	–	–	–	–
1943	9.90	9.51	16.3	66.1	28.8M	25.7	26.55	26.99	–	–	–	–	–
1944	9.59	9.55	9.6m	69.7	20.7	25.6	26.96	27.00	–	–	–	–	–
1945	10.29	9.59	33.2	72.8	19.3m	25.5	26.44	26.90	–	–	–	–	–
1946	9.32	9.58	92.6	74.7	28.3	25.7	26.85	26.76	–	–	–	–	–
1947	9.15	9.55	151.6M	75.9	28.1	26.2	26.80	26.72	–	–	–	–	–
1948	9.71	9.52	136.3	75.8	25.5	26.3	27.14	26.78	–	–	–	–	–
1949	10.33	9.50	134.7	75.4	24.1	26.1	26.57	26.80	–	–	–	–	–
1950	9.17	9.44	83.9	75.4	27.3	26.1	26.00	26.74	–	–	–	–	–
1951	8.96	9.40	69.4	78.1	31.7M	26.1	27.19	26.68	–	–	–	–	–
1952	8.82	9.44	31.5	82.5	30.8	26.2	26.88	26.69	–	–	–	–	–
1953	9.87	9.46	13.9	86.8	25.1	26.4	27.38	26.74	–	–	–	–	–
1954	9.16	9.44	4.4m	90.5	20.2m	26.8	26.48	26.79	–	–	–	–	–
1955	9.49	9.45	38.0	93.1	20.5	27.4	25.88	26.86	–	–	–	–	–
1956	9.38	9.49	141.7	93.7	27.6	27.2	26.20	26.89	–	–	–	–	–
1957	9.84	9.52	190.2M	93.3	29.3	26.2	27.55	26.87	–	–	–	–	–
1958	9.45	9.45	184.8	94.3	28.4	25.6	27.49	26.86	(315.23)	–	–	–	–
1959	10.21	9.41	159.0	95.3	30.1	25.2	27.05	26.87	315.98	–	–	–	–
1960	9.44	9.39	112.3	94.4	32.8M	24.7	26.97	26.96	316.91	–	–	–	–
1961	9.58	9.36	53.9	88.5	22.3	23.9	26.87	27.10	317.64	–	–	–	–
1962	8.77	9.33	37.6	79.0	21.4	22.9	26.73	27.11	318.45	–	–	–	–
1963	8.57	9.30	27.9	70.2	21.2	22.1	27.42	27.05	318.99	318.99	–	–	–
1964	9.49	9.23	10.2m	63.6	17.1	21.3	26.52	27.05	(319.20)	319.81	–	–	–
1965	8.82	9.16	15.1	60.5	14.0m	20.2	27.66	27.07	320.04	320.68	–	–	–
1966	9.38	9.16	47.0	60.8	17.3	19.4	27.29	27.02	321.38	321.56	–	–	–
1967	9.40	9.17	93.8	63.0	19.7	19.3	26.68	27.04	322.16	322.44	–	–	–

Table 1. Annual and 10-yma values of ASAT, SSN, Aa, N3.4, and MLCO2, and selected percentages (continued).

Year	ASAT	10-yma	SSN	10-yma	Aa	10-yma	N3.4	10-yma	MLCO2	10-yma	P1	P2	P3
1968	9.32	9.20	105.9M	65.0	22.5	19.5	27.04	27.04	323.05	323.42	–	–	–
1969	8.93	9.21	105.5	66.8	19.9	20.4	27.62	26.97	324.63	324.51	–	–	–
1970	9.29	9.23	104.5	68.0	19.9	21.6	26.71	26.87	325.68	325.62	–	–	–
1971	9.72	9.27	66.6	66.3	20.0	22.3	26.13	26.77	326.32	326.71	–	–	–
1972	8.74	9.25	68.9	61.3	20.5	22.6	27.84	26.80	327.45	327.84	–	–	–
1973	9.33	9.22	38.0	57.3	26.7	22.7	26.41	26.83	329.68	329.05	–	–	–
1974	8.94	9.18	34.5	59.1	30.3M	23.0	26.12	26.81	330.25	330.28	–	–	–
1975	9.70	9.15	15.5	64.1	23.7	23.1	26.02	26.81	331.15	331.54	–	–	–
1976	9.34	9.11	12.6m	70.3	22.2	23.2	26.98	26.88	332.15	332.88	–	–	–
1977	8.92	9.11	27.5	76.3	20.2m*	24.1	27.56	26.92	333.90	334.24	–	–	–
1978	9.21	9.17	92.5	80.1	25.5	25.0	26.88	26.98	335.51	335.58	–	–	–
1979	8.36	9.21	155.4M	82.1	22.4	25.0	27.25	27.05	336.85	336.94	0.602	0.848	0.906
1980	9.11	9.17	154.6	82.8	18.5m	24.9	27.20	27.07	338.69	338.39	0.603	0.846	0.903
1981	9.09	9.08	140.4	83.0	24.7	24.8	26.87	27.10	339.93	339.88	0.601	0.842	0.901
1982	9.44	9.05	115.9	83.1	33.9M	24.6	27.98	27.15	341.13	341.38	0.596	0.838	0.897
1983	9.77	9.08	66.6	83.6	29.5	24.4	27.51	27.14	342.78	342.93	0.597	0.835	0.894
1984	9.29	9.19	45.9	84.1	28.8	24.6	26.34	27.05	344.42	344.53	0.598	0.833	0.891
1985	8.70	9.32	17.9	83.6	22.5	25.4	26.35	27.00	345.90	346.11	0.597	0.830	0.887
1986	8.57	9.38	13.4m	83.3	21.1	26.3	27.15	27.04	347.15	347.67	0.595	0.825	0.883
1987	9.07	9.39	29.4	82.4	18.9m	26.5	28.29	27.07	348.93	349.21	0.595	0.822	0.879
1988	9.66	9.37	100.2	80.8	22.1	25.9	26.04	27.05	351.48	350.69	0.598	0.820	0.877
1989	10.07	9.35	157.6M	79.4	30.3	25.8	26.27	27.11	352.91	352.12	0.596	0.816	0.873
1990	9.94	9.43	142.6	78.5	26.6	25.8	27.24	27.20	354.19	353.59	0.594	0.812	0.870
1991	9.43	9.54	145.7	78.3	34.2M	25.6	27.66	27.21	355.59	355.12	0.594	0.810	0.869
1992	9.45	9.64	94.3	77.6	27.3	25.4	27.69	27.18	356.37	356.63	0.592	0.807	0.866
1993	9.27	9.72	54.6	75.5	25.5	25.2	27.50	27.24	357.04	358.13	0.592	0.806	0.865
1994	9.38	9.75	29.9	70.4	29.4*	24.7	27.44	27.28	358.89	359.66	0.594	0.806	0.865
1995	10.23	9.75	17.5	66.1	22.0	24.2	27.04	27.21	360.88	361.19	0.597	0.807	0.866
1996	9.23	9.76	8.6m	63.2	18.6	23.6	26.69	27.11	362.64	362.73	0.600	0.807	0.867
1997	10.33	9.80	21.5	61.9	16.1m	22.8	28.25	27.06	363.76	364.34	0.601	0.807	0.867
1998	10.09	9.88	64.3	62.9	21.0	23.1	27.14	27.05	366.63	366.11	0.606	0.809	0.869
1999	10.18	9.96	93.3	63.9	22.2	23.4	25.97	27.04	368.31	367.96	0.609	0.810	0.870
2000	9.93	10.00	119.6M	65.0	25.4	23.1	26.19	27.04	369.48	369.82	0.610	0.810	0.871
2001	9.58	10.06	111.0	66.0	22.4	23.1	26.73	27.07	371.02	371.72	0.613	0.810	0.871
2002	10.20	10.13	104.0	65.6	22.7	22.9	27.65	27.00	373.10	373.67	0.616	0.811	0.873
2003	10.02	10.13	63.7	61.8	37.1M	22.5	27.30	26.88	375.64	375.60	0.620	0.813	0.874
2004	10.21	–	40.4	–	23.1	–	27.43	–	377.38	–	0.623	0.814	0.875
2005	10.24	–	29.8	–	23.2*	–	27.10	–	379.67	–	0.627	0.815	0.876
2006	10.43	–	15.2	–	16.2	–	27.16	–	381.84	–	0.619	0.815	0.877
2007	10.59	–	7.5	–	15.0	–	26.50	–	383.55	–	0.632	0.816	0.878
2008	9.78	–	2.9	–	14.2	–	26.35	–	385.34	–	0.635	0.817	0.880

Table 1. Annual and 10-yma values of ASAT, SSN, Aa, N3.4, and MLCO2, and selected percentages (continued).

Year	ASAT	10-yma	SSN	10-yma	Aa	10-yma	N3.4	10-yma	MLCO2	10-yma	P1	P2	P3
Mean	9.24	9.20	56.0	56.4	21.4	21.4	26.95	26.97	345.04	344.18	–	–	–
sd	0.54	0.33	43.8	18.2	5.6	3.5	0.57	0.15	21.24	17.17	–	–	–

Note: m means minimum value.
m* means alternate minimum value in vicinity of sunspot cycle minimum.
M means maximum value.
M* means alternate maximum value during decline of sunspot cycle.
*means alternate maximum value closer to sunspot cycle minimum.
Aa refers to the Aa–geomagnetic index, increased by 3 nT for years prior to 1957.
N3.4 refers to the HadSST value for the Niño 3.4 region.
MLCO2 gives CO_2 in parts per million by volume as measured at Maun Loa Observatory in Hawaii <http://cdiac.ornl.gov/ftp/trends/co2/maunaloa.co2>; annual means for 1958 and 1964 are based on 10 and 9 mo, respectively.

Figure 2 displays the inferred bivariate fit of ASAT against Aa and MLCO2 for the common interval 1963–2003. The inferred correlation is extremely strong, having $r = 0.948$ (inferring that nearly 90% of the variance in ASAT can be explained by the combined variations of Aa and MLCO2) and $se = 0.11$ °C. The occurrences of significant volcanic eruptions are across the top of the chart (those having a volcanic explosivity index (VEI) ≥4), strong El Niño (EN) events (those having an anomaly 1.5 °C or warmer using the Hadley Sea Surface Temperature (HadSST1) dataset), and strong La Niña (LN) events (those having an anomaly –1.5 °C or cooler using the HadSST1 dataset), where the EN and LN event occurrence year is determined as the year when the anomaly was at greatest strength.[20] Table 2 provides a convenient listing of significant volcanic eruptions[21] and table 3 identifies the occurrences of strong EN and LN events[22] for the expanded interval 1870–2003. A bivariate fit using N3.4 and MLCO2 does not improve the correlation as compared to the single-variate fit of using MLCO2 alone.

Figure 3(a) depicts the estimated 10-yma values of MLCO2 using the inferred bivariate fit (B1) identified in figure 2 for the expanded interval 1873–2003. Since ASAT and Aa are both known, one can estimate MLCO2 using the fit. Also plotted are the observed MLCO2 values for the interval 1963–2003 and the occurrences of significant volcanic eruptions and strong EN and LN events (taken from tables 2 and 3). Certainly, the observed and estimated MLCO2 values are in reasonably close agreement for 1963–2003, with slight discrepancies possibly being associated with the occurrences of significant volcanic eruptions and/or strong EN southern oscillation (ENSO) events. Even the values prior to about 1925 seem somewhat reasonable to the unaided eye, if one ignores the values between 1925 and 1965, suggesting an exponential rise in MLCO2, but one that possibly is steepening with the passage of time. It is the anomalous interval between 1925 and 1965 that proves troublesome. Presuming the veracity of the bivariate fit, one is led to conclude either that the ASAT or Aa values might be in error during the interval or that the atmospheric CO_2 concentration unexpectedly rose steeply, reached a plateau, then fell prior to the 1963–2003 rise. Indeed, values of Aa have been slightly increased by 3 nT prior to 1957, to account for relocations of the magnetometers used to derive the Aa values,[12] which has improved certain correlations related to Aa but does not appreciably alter the estimated MLCO2 values. Likewise, ASAT during this timespan is well-calibrated and agrees with anomalies as depicted in the Goddard Institute for Space Studies surface temperature analyses,[23] in other European temperature records,[24] and in sea-surface temperature trends,[25]

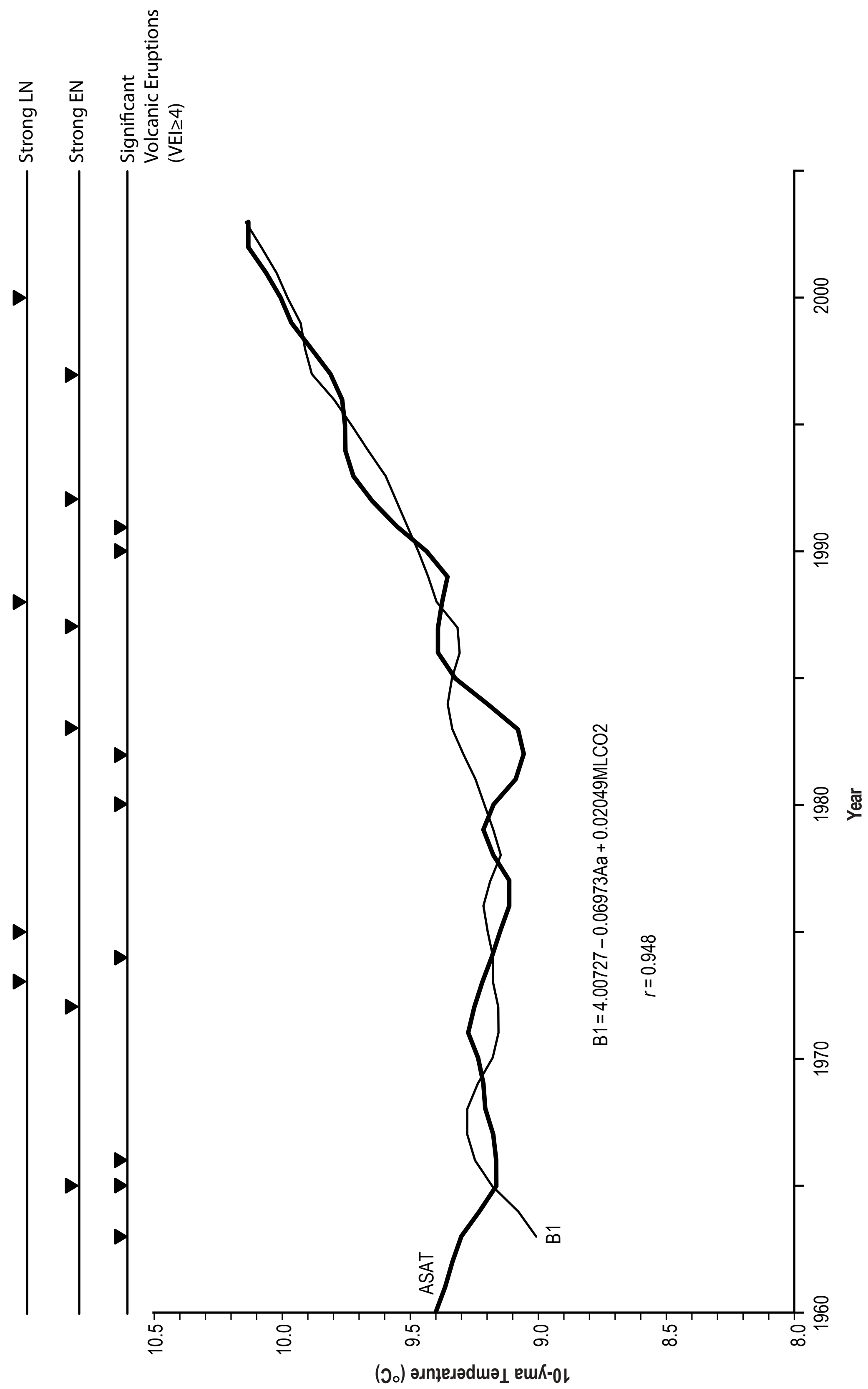

Figure 2. The bivariate fit of 10-yma values of ASAT using Aa and MLCO2 for the interval 1963–2003.

Table 2. Significant volcanic eruptions (VEI ≥ 4).

Year	Month	Day	Name	Location	VEI
1872	11	3	Merapi	Java	4
1877	6	25	Cotopaxi	Ecuador	4
1883	8	26	Krakatau	Indonesia	6
1883	10	6	Augustine	Alaska-SW	4
1886	1	11	Tungurahua	Ecuador	4
1886	8	31	Niuafo'ou	Tonga-SW Pac	4
1888	7	15	Bandai	Honshu-Japan	4
1899	11	13	Dona Juana	Columbia	4
1902	5	7	Soufriere St. Vincent	W. Indies	4
1902	5	8	Pelee	W. Indies	4
1902	8	30	Pelee	W. Indies	4
1902	10	24	Santa Maria	Guatemala	6
1911	1	27	Taal	Luzon-Philippines	4
1913	9	-	Novarupta	Alaska Peninsula	6
1914	1	12	Sakura-jima	Kyushu-Japan	4
1919	5	19	Kelut	Java	4
1929	6	17	Komaga-take	Hokkaido-Japan	4
1933	12	24	Kuchinoerabu-jima	Ryukyu Is	4
1937	5	29	Rabaul	New Britain-SW Pac	4
1943	2	20	Michoacan-Guanajuto	Mexico	4
1947	11	2	Hekla	Iceland-S	4
1951	1	15	Lamington	New Guinea	4
1955	7	26	Carran-Los Venados	Chile-C	4
1956	3	30	Bezymianny	Kamchatka	5
1963	2	19	Agung	Lesser Sundra Is	4
1965	9	28	Taal	Luzon-Philippines	4
1966	4	26	Kelut	Java	4
1966	8	12	Awu	Sangihe Is-Indonesia	4
1966	8	14	Lengai, Ol Doinyo	Africa-E	4
1974	10	10	Fuego	Guatemala	4
1980	5	18	St. Helens	US-Washington	5
1982	3	28	El Chichon	Mexico	5
1982	4	4	El Chichon	Mexico	5
1982	5	17	Galungung	Java	4
1982	5	27	El Chichon	Mexico	4
1990	2	10	Kelut	Java	4
1991	6	15	Pinatubo	Luzon-Philippines	6

*Adapted from National Geophysical Data Center

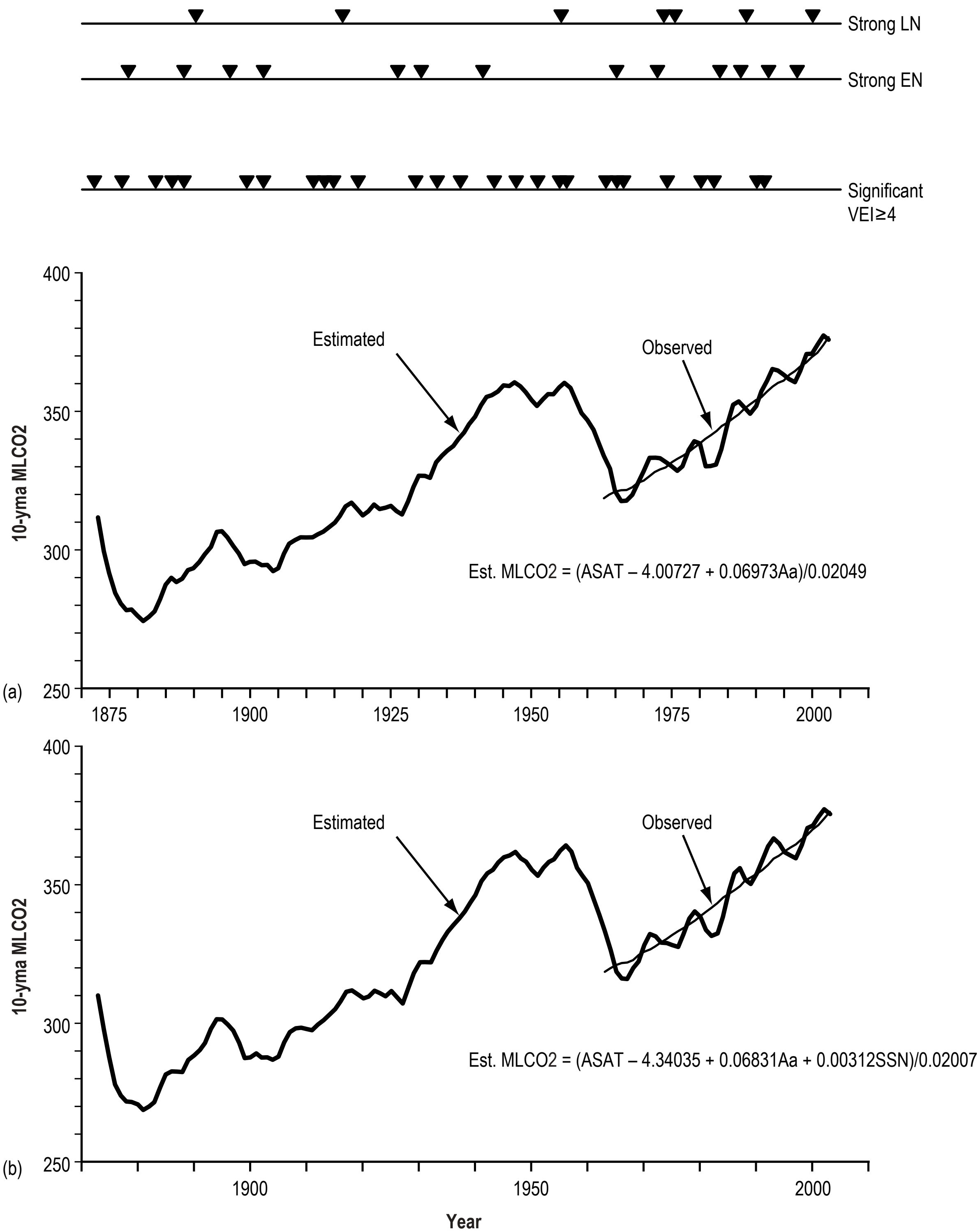

Figure 3. Estimated 10-yma values of MLCO2 for the interval 1873–2003, using (a) bivariate and (b) trivariate fits, and significant volcanic eruptions and occurrences of strong EN and LN events.

Table 3. Strong EN and LN events.

Start	Max	End	Type
1877-02	1878-01	1878-06	EN
1888-02	1888-11	1889-04	EN
1889-08	1890-01	1890-12	LN
1896-07	1896-12	1897-03	EN
1902-05	1902-11	1903-04	EN
1916-07	1916-12	1917-03	LN
1925-07	1926-01	1926-07	EN
1930-07	1930-11	1931-07	EN
1940-11	1941-04	1942-03	EN
1954-06	1955-11	1956-12	LN
1965-06	1965-11	1966-04	EN
1972-05	1972-11	1973-03	EN
1973-06	1973-12	1974-06	LN
1975-04	1975-12	1976-03	LN
1982-05	1983-01	1983-06	EN
1986-09	1987-09	1988-01	EN
1988-05	1988-11	1989-06	LN
1991-05	1992-01	1992-06	EN
1997-04	1997-11	1998-05	EN
1999-07	2000-01	2000-06	LN
2007-08	2008-01	2008-05	LN

*Based on HadSST1 dataset.

so ASAT is considered correct. The anomalous interval 1925–1965 corresponds to an interval of rapid growth in the strength of solar cycles (cycles 16–19, with cycle 19 being the strongest on record). Perhaps, an additional factor (SSN) might have to be included during this interval (e.g., 10-yma values of SSN rose from 40 to 95 between 1930 and 1959).

Figure 3(b) displays the estimated 10-yma values of MLCO2 for the interval 1873–2003, based on a trivariate fit for the interval 1963–2003, one that incorporates 10-yma values of Aa, SSN, and MLCO2. The trivariate fit has a slightly larger r (=0.952) and smaller se (=0.1 °C) than the bivariate fit, and is given as $T = ASAT = 4.34035 - 0.06831Aa - 0.00312SSN + 0.02007MLCO2$. The estimated MLCO2 values found using the trivariate fit are quite similar to that found using the bivariate fit, although slightly lower values are inferred prior to about 1945 and slightly higher values are inferred during the interval 1945 to about 1963. Consequently, the mystery remains. Is the inferred increase in atmospheric CO_2 concentration real, or has the bump in ASAT during the mid 20th century been caused by some other unknown effect? Observed values from 1963 to the present are closely approximated by both the bivariate and trivariate fits. Because 10-yma values of Aa and SSN probably will be decreasing in the near term before increasing due to strengthening of sunspot cycle 24, the 10-yma value of ASAT might level off or even slightly decline, unless, of course, the 10-yma value of MLCO*2* continues to increase unabated.

3. SUMMARY

Global warming is proving to be a rather pernicious problem, one that must be dealt with sooner rather than later, for its continued unabated rise will greatly alter ecological habitats and human lifestyle.[9–11,26–28] Ten-yma surface-air temperatures, as recorded at Armagh Observatory, Northern Ireland, have documented the rise over the past 165 yr. Today (i.e., 2003, the last available 10-yma value), the temperature measures 10.13 °C, a value that exceeds the long-term mean by 0.93 °C. While the overall trend in Armagh 10-yma values can be fit linearly for the interval 1883–2003 as ASAT = –5.251 + 0.00746t for r = 0.792, the trend since 1982 has been much steeper (ASAT = –91.185 + 0.05059t for r = 0.989), indicating a potential rise to 2 °C above the long-term mean in about the year 2024.

Comparisons of ASAT against SSN, Aa, N3.4, and MLCO2 reveal strong correlation to exist against the solar cycle indices, in particular, Aa, especially for the interval prior to about 1980 (ASAT = 7.807 + 0.063Aa for r = 0.762), weak correlation against N3.4, and very strong correlation against MLCO2 (ASAT = 3.664 + 0.017MLCO2 for r = 0.877). A bivariate fit using Aa and MLCO2 is found to be even stronger (ASAT = 4.00727 – 0.06973Aa + 0.02049MLCO2 for r = 0.948) and a trivariate fit using Aa, SSN, and MLCO2 is inferred to be stronger still (ASAT = 4.34035 – 0.06831Aa – 0.00312SSN + 0.02007MLCO2 for r = 0.952).

Extrapolating the bivariate (or trivariate) fit backwards in time results in estimates of CO_2 atmospheric concentration in close agreement with preindustrial levels (about 280 ppmv), although an anomalous peak in CO_2 atmospheric concentration is inferred to have occurred about 1925–1965, indicating that CO_2 levels were enhanced during this 40 yr interval, an interval associated with a strengthening of sunspot cycles (cycles 16–19). Extrapolation of the bivariate (or trivariate) fit forwards in time suggests that ASAT could be about 2 °C warmer than its long-term mean within about 20 yr (from 2003), using a 10-yma value of Aa = 17 (equivalent to that found for cycle 14, the smallest cycle in the modern record) and a 10-yma value of MLCO2 = 407 ppmv (from extrapolation of the exponential fit, log(MLCO2) = –0.971 + 0.00177t). If CO_2 atmospheric concentration increases more rapidly, then the 2 °C threshold would be attained more quickly. Similarly, if emission levels of CO_2 (and other greenhouse gases) can be quickly stabilized, then the effect on ASAT (and, hence, the inferred trend of global temperature) could be ameliorated. Certainly, it now appears that anthropogenic forcing due to increasing greenhouse gas concentration is the main culprit of the current trend in surface-air temperature (i.e., global warming), in contrast to an earlier time when the solar cycle appeared to be more dominant. In fact, CO_2 atmospheric concentration is higher now than at anytime in the past 130 yr.

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14. ABSTRACT
A comparison of 10-yr moving average (yma) values of Armagh Observatory (Northern Ireland) surface-air temperatures with selected solar cycle indices (sunspot number (SSN) and the Aa geomagnetic index (Aa)), sea-surface temperatures in the Niño 3.4 region, and Mauna Loa carbon dioxide (CO_2) (MLCO2) atmospheric concentration measurements reveals a strong correlation ($r = 0.686$) between the Armagh temperatures and Aa, especially, prior to about 1980 ($r = 0.762$ over the interval of 1873–1980). For the more recent interval 1963–2003, the strongest correlation ($r = 0.877$) is between Armagh temperatures and MLCO2 measurements. A bivariate fit using both Aa and Mauna Loa values results in a very strong fit ($r = 0.948$) for the interval 1963–2003, and a trivariate fit using Aa, SSN, and Mauna Loa values results in a slightly stronger fit ($r = 0.952$). Atmospheric CO_2 concentration now appears to be the stronger driver of Armagh surface-air temperatures. An increase of 2 °C above the long-term mean (9.2 °C) at Armagh seems inevitable unless unabated increases in anthropogenic atmospheric gases can be curtailed. The present growth in 10-yma Armagh temperatures is about 0.05 °C per yr since 1982. The present growth in MLCO2 is about 0.002 ppmv, based on an exponential fit using 10-yma values, although the growth appears to be steepening, thus, increasing the likelihood of deleterious effects attributed to global warming.

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