NASA/TP—2006–214434

Examination of the Armagh Observatory Annual Mean Temperature Record, 1844–2004

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July 2006

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Space Administration

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NOMENCLATURE

aa	annual aa-geomagnetic index
aa_{10}	10-year moving average of the aa-geomagnetic index
$\langle aa \rangle$	average aa over a sunspot cycle
$\langle\langle aa \rangle\rangle$	average aa over a Hale cycle
$\langle aa \rangle_2$	2-cycle moving average of $\langle aa \rangle$
°C	degrees Centigrade
cl	confidence level
r	coefficient of correlation
r^2	coefficient of determination (amount of variance explained by the inferred regression)
R	annual sunspot number
R_{10}	10-year moving average of sunspot number
$\langle R \rangle$	average R over a sunspot cycle
$\langle\langle R \rangle\rangle$	average R over a Hale cycle
$\langle R \rangle_2$	2-cycle moving average of $\langle R \rangle$
se	standard error of estimate
t	the t-statistic for independent samples
T	annual mean temperature at Armagh Observatory
T_{10}	10-year moving average of T
$\langle T \rangle$	average T over a sunspot cycle
$\langle T \rangle_{aa}$	the inferred regression for $\langle T \rangle$ versus $\langle aa \rangle$

NOMENCLATURE (Continued)

$\langle T \rangle_{aa2}$	the inferred regression for $\langle T \rangle_2$ versus $\langle aa \rangle_2$
$\langle T \rangle_R$	the inferred regression for $\langle T \rangle$ versus $\langle R \rangle$
$\langle T \rangle_{R2}$	the inferred regression for $\langle T \rangle_2$ versus $\langle R \rangle_2$
$\langle\langle T \rangle\rangle$	the average T over a Hale cycle
$\langle T \rangle_2$	2-cycle moving average of $\langle T \rangle$
$T_{10}(aa_{10})$	the inferred regression of T_{10} versus aa_{10}
$T_{10}(\mathrm{R}_{10})$	the inferred regression of T_{10} versus R_{10}
x	the independent variable
y	the dependent variable

TECHNICAL PUBLICATION

EXAMINATION OF THE ARMAGH OBSERVATORY ANNUAL MEAN TEMPERATURE RECORD, 1844–2004

1. INTRODUCTION

The Armagh Observatory temperature record is one of the longest available for study.[1–3] Mean temperature readings based on maximum and minimum thermometers extend from 1844 to the present, where mean temperature is defined as the mean of the daily maximum and minimum temperatures.

Armagh Observatory[3] lies about 1 km northeast of the center of the ancient city of Armagh in Northern Ireland, being located at latitude 54°21.2´N and longitude 6°38.9´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. Studies have shown that its rural environment has ensured that the observatory suffers from little or no urban microclimatic effects[4] and that the temperature readings can be used as a proxy for studying long-term trends in annual mean temperature for the northern hemisphere and globe.[2,3]

The purpose of this study, then, is to examine the extended Armagh Observatory annual mean temperature record spanning 1844–2004, investigating trends in the data indicative of climatic change. In particular, this study updates a previous one that was based on the Armagh data spanning 1844–1992.[2]

2. RESULTS AND DISCUSSION

Figure 1 displays the Armagh Observatory annual mean temperature T (1844–2004) in the lower panel, in comparison with the annual mean *aa*-geomagnetic index (1868–2004) in the middle panel and the annual mean sunspot number R (1840–2004) in the top panel, all drawn as thin lines. Ten-year moving averages of each are drawn as the thick lines, and the numbers appearing in the top panel refer to sunspot cycle numbers 9–23.

Concerning T, it has a mean of 9.215 °C, a standard deviation of 0.521 °C and a median of 9.20 °C. For the interval 1844–2004, 82 values of T are equal to or above the median and 79 values of T are less than the median, occurring in 65 runs. Based on these values, one finds that T appears to be distributed nonrandomly at the 2-percent level of significance (or 98-percent confidence level (cl)).[5] Furthermore, the average T for the first half of the record (1844–1923) is significantly lower than the average for the latter half of the record (1924–2004) at the 0.1-percent level of significance (or 99.9-percent cl), based on the t-statistic for independent samples.[6] During the first half of the record, the average T measured 9.028 °C, having a standard deviation of 0.518 °C, while during the latter half it measured 9.400 °C, having a standard deviation of 0.455 °C. Thus, there has been a significant warming that appears to vary systematically rather than randomly.

The highest T occurred in 1846 and measured 10.40 °C, while the lowest T occurred in 1879 and measured 7.40 °C. The highest T_{10} (10-year moving average of T) occurred in 1999 (the last entry) and measured 9.95 °C, while the lowest T_{10} occurred in 1883 and measured 8.44 °C. Thus, from 1883 to 1999, T_{10} has increased 1.51 °C, and for 7 of the last 10 years (ending in 2004), T has exceeded 10 °C, unprecedented in the preceding years of the temperature record.

Concerning T_{10}, one finds that it decreased rather smoothly from 1849 (its first entry), having a value of 9.45 °C, to 1883 when the lowest value was seen. This was followed by a rather steady increase to a local peak of 9.58 °C in 1945, a slight decrease between 1945 and 1982 (to 9.05 °C) and then a sharp increase to its highest value recorded so far (through 1999, the end of the T_{10} record).

For the contemporaneous interval 1868–2004, T correlates strongly with both aa ($r=0.34$, $se=0.44$ °C) and R ($r=0.24$, $se=0.51$ °C), while for the contemporaneous interval 1873–1999 T_{10} correlates strongly with aa_{10} ($r=0.71$, $se=0.22$ °C) and R_{10} ($r=0.67$, $se=0.23$ °C), where the subscript 10 refers to the 10-year moving average (aa_{10} correlates strongly with R_{10}, having $r=0.933$). The inferred regression for T versus aa is $T=8.639 + 0.029\ aa$; the inferred regression for T versus R is $T= 9.044+0.003\ R$; the inferred regression for T_{10} versus aa_{10} is $T_{10}=8.190+0.051\ aa_{10}$; and the inferred regression for T_{10} versus R_{10} is $T_{10}=8.562\ +0.011\ R_{10}$. A bivariate analysis using both aa_{10} and R_{10} results in $\mathrm{T}_{10}=8.205 + 0.048\ aa_{10}+0.001\ R_{10}$, having a correlation coefficient of 0.71 and a standard error of estimate of 0.22 °C (the bivariate fit offers no significant improvement over the single-variate fits).

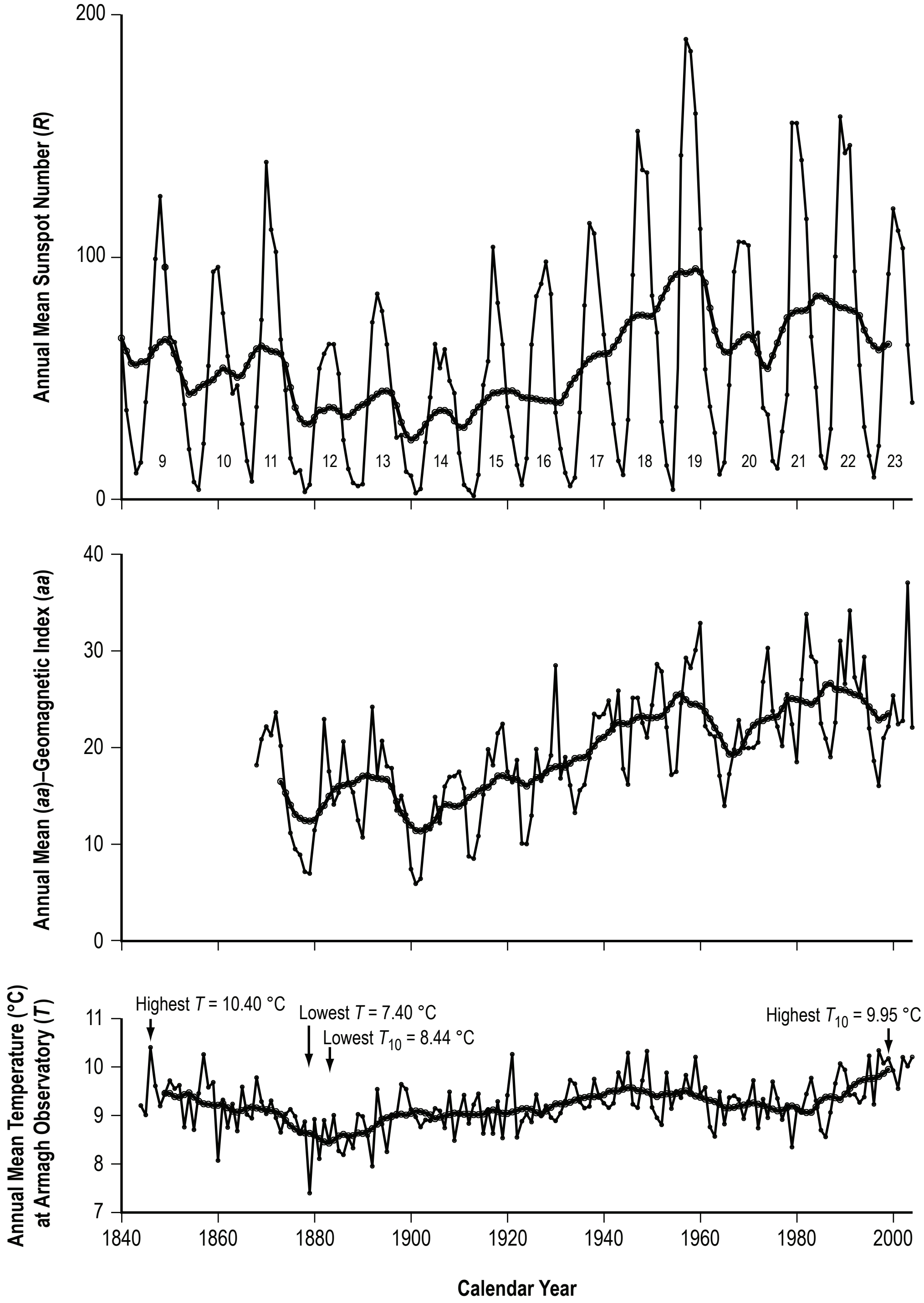

Figure 1. Annual mean variation of Armagh Observatory temperature, *T* (lower panel); the *aa*-geomagnetic index, *aa* (middle panel); and sunspot number, *R* (upper panel). The thin lines are the annual means and the thick lines are the 10-year moving averages. The numbers 9–23 in the upper panel refer to sunspot cycles 9–23. See text for additional remarks.

Figure 2 depicts the residual $T_{10}–T_{10}(aa_{10})$ in the lower panel and the residual $T_{10}–T_{10}(R_{10})$ in the upper panel, where $T_{10}(aa_{10})$ and $T_{10}(R_{10})$ are the inferred regressions between T_{10} and aa_{10} and between T_{10} and R_{10}, respectively. The residuals (having removed the solar/geomagnetic forcing, which accounts for about half the variance) suggest episodic variation in the temperature record, with a cooler interval in the early portion between about 1873 and 1896; a fairly steady, though slowly varying signal (possibly related to the North Atlantic Oscillation[3]) between about 1896 and 1970; another brief interval of cooling between about 1970 and 1990; and a rapid warming after about 1990. It should be noted that T_{10} for 1999 (the end of the record and the highest inferred value) is greater than 2.6 standard deviations higher than what T_{10} should be, based on the $T_{10}(aa_{10})$ fit and greater than 3 standard deviations higher than what T_{10} should be, based on the $T_{10}(R_{10})$ fit. Thus, the observed warming is beyond that which one would expect from simple solar/geomagnetic forcing.[7]

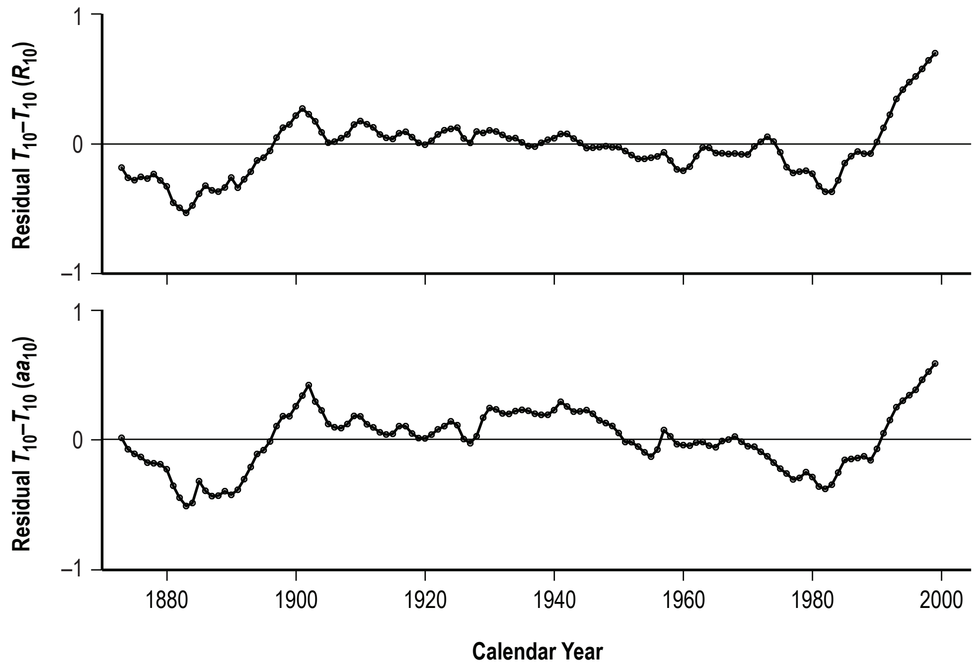

Figure 2. The residual $T_{10} – T_{10}(aa_{10})$ (lower panel) and $T_{10} – T_{10}(R_{10})$ (upper panel), where T_{10} is the 10-year moving average of temperature and $T_{10}(aa_{10})$ and $T_{10}(R_{10})$ are the regression fits (T_{10} versus aa_{10} and T_{10} versus R_{10}). See text for details.

Figure 3 shows another way of illustrating the temperature record. The lower panel displays the sunspot cyclic average (from sunspot minimum to minimum) of temperature <*T*> versus sunspot cycle number, in comparison to cyclic averages of the *aa*-geomagnetic index <*aa*> (middle panel) and sunspot number <*R*> (upper panel). The thin line in each panel refers to the cyclic averages and the thick line refers to the 2-cycle moving average (the 2-cycle moving average,[8] or 3-cycle running mean, is computed with a weighting of 1:2:1 and can be used as a proxy for the Hale cycle average, where the Hale cycle refers to two successive sunspot cycles[9]). There is a striking similarity in the various curves, especially the 2-cycle moving averages.

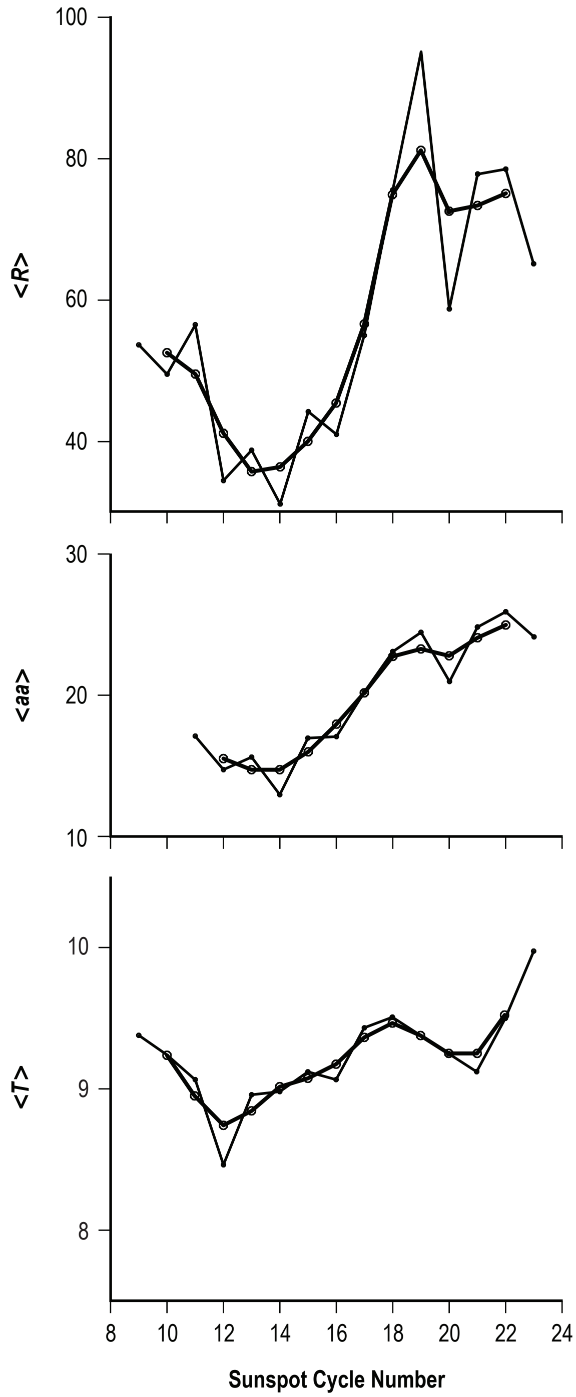

Figure 3. Variation of temperature <*T*> (lower panel), the *aa*-geomagnetic index <*aa*> (middle panel), and sunspot number <*R*> (upper panel) averaged over each sunspot cycle 9–23. The thin line is the cyclic average and the thick line is a 2-cycle moving average. See text for details.

From figure 3, one surmises that $\langle T \rangle_2$ (the 2-cycle moving average of temperature) was lowest in cycle 12, which spans the years 1878–1888. This was followed by a steady rise in $\langle T \rangle_2$ between cycles 12 and 18, then a slight dip in $\langle T \rangle_2$ for cycles 20 and 21 before rising again in cycle 22, which has the highest $\langle T \rangle_2$ in the record, although, plainly, its value will be exceeded in cycle 23, since cycle 23 has the highest $\langle T \rangle$ for all sunspot cycles. ($\langle T \rangle$ for cycle 23 will change slightly, since the temperature record ends in 2004 and, therefore, does not include the annual average of T for the year 2005.)

Figure 4 displays scatterplots of $\langle T \rangle$ versus $\langle aa \rangle$ (lower-left panel), $\langle T \rangle$ versus $\langle R \rangle$ (lower-right panel), $\langle T \rangle_2$ versus $\langle aa \rangle_2$ (upper-left panel) and $\langle T \rangle_2$ versus $\langle R \rangle_2$ (upper-right panel). All inferred regressions are statistically significant, strongly suggesting that trends in the solar/geomagnetic cycle strongly influence temperature trends on the Earth. In particular, 75 percent of the variance in $\langle T \rangle_2$ can be explained by the variation of $\langle aa \rangle_2$. (In figure 4, the large filled circle in the $\langle T \rangle$ versus $\langle aa \rangle$ scatterplot simply means that two cycles had identical entries, cycles 11 and 16.)

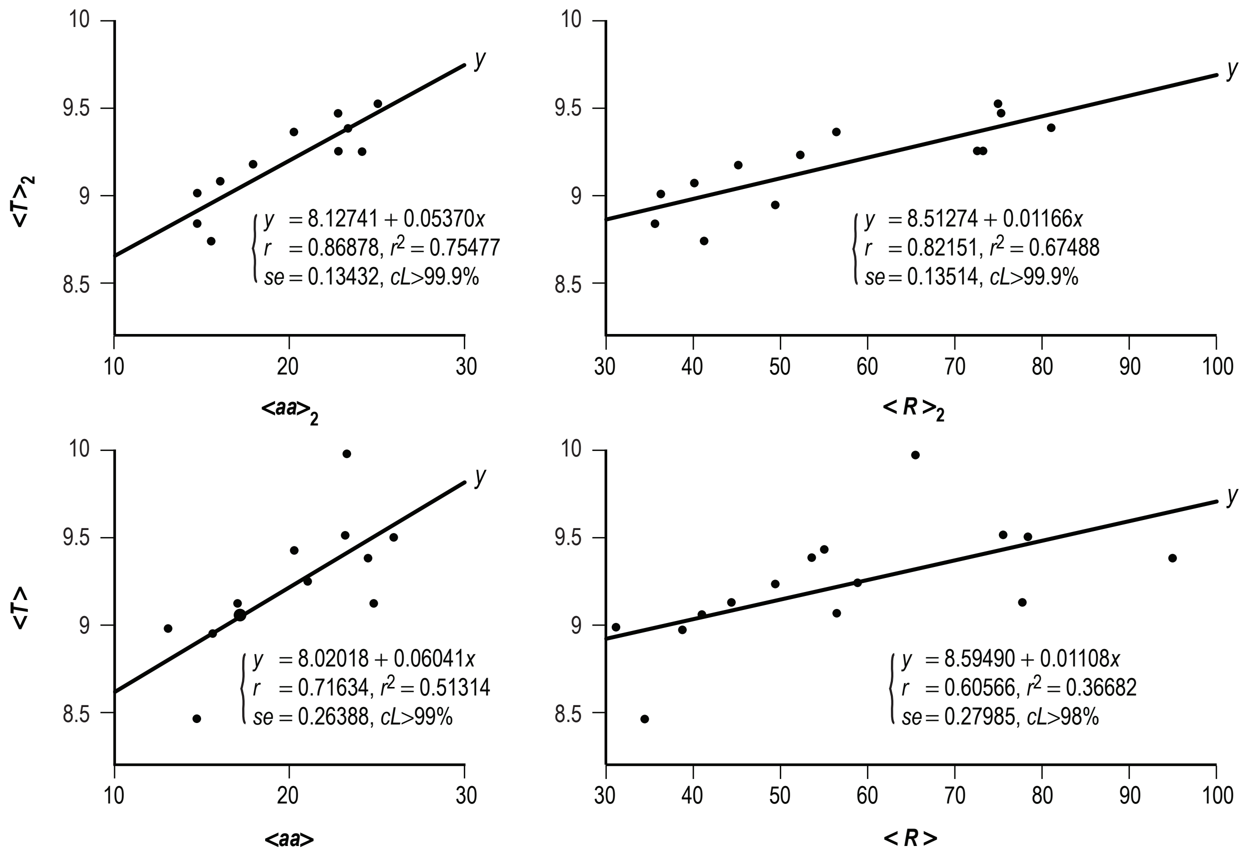

Figure 4. Scatterplots of $\langle T \rangle$ versus $\langle aa \rangle$ (lower-left panel), $\langle T \rangle$ versus $\langle R \rangle$ (lower-right panel), $\langle T \rangle_2$ versus $\langle aa \rangle_2$ (upper-left panel) and $\langle T \rangle_2$ versus $\langle R \rangle_2$ (upper-right panel). See text and nomenclature for details.

Figure 5 shows the residuals of cyclic temperature, having removed the effects of the solar/geomagnetic cycle. The lower panel shows the residual $<T>-<T>_{aa}$, where $<T>_{aa}$ is the regression fit for $<T>$ versus $<aa>$; the lower-middle panel shows the residual $<T>_2-<T>_{aa2}$, where $<T>_{aa2}$ is the regression fit for $<T>_2$ versus $<aa>_2$; the upper-middle panel shows the residual $<T>-<T>_R$, where $<T>_R$ is the regression fit for $<T>$ versus $<R>$; and the upper panel shows the residual $<T>_2 - <T>_{R2}$, where $<T>_{R2}$ is the regression fit for $<T>_2$ versus $<R>_2$. The residual is most negative in cycles 12 and 21, suggesting, perhaps, a 9-cycle variation in temperature. Such a variation may be related to a supposed 90–100 year variation, believed to be embedded in the solar/geomagnetic record.[10–12] The residual for cycle 23 based on $<aa>$ or $<R>$ is 0.55 °C and 0.65 °C, respectively, both being greater than 2 standard deviations higher than that suggested by the regression fits. Hence, during cycle 23 temperatures on Earth are significantly warmer than can be explained simply by solar/geomagnetic forcing.

Because of the highly significant correlations between $<T>_2$ and both $<aa>_2$ and $<R>_2$, it is apparent that temperature is possibly related to the Hale cycle, either to the strength of the Hale cycle or, perhaps, its length (a Hale cycle consists of two successive sunspot cycles, where the magnetic polarities of leading and following sunspots in each of the Sun's northern and southern hemisphere reverse from one sunspot cycle to the next, with positive magnetic fields leading in odd-numbered sunspot cycles in the northern hemisphere). Figure 6 depicts the scatterplots of $<<T>>$ even-odd cycles versus $<T>$ even-leading cycle for each Hale cycle pair, grouped as even-odd cycle pairs (left panel) and $<<T>>$ odd-even cycles versus $<T>$ odd-leading cycle for each Hale cycle pair, grouped as odd-even cycle pairs (right panel). The inferred correlation appears strongest for the even-odd cycle grouping, although both regressions are statistically important. The large filled circle in the right panel simply means that two entries were identical for odd-even cycle pairs 9–10 and 19–20. Also, it should be noted that since an estimate of $<T>$ can be made for cycle 23, having $<T>=9.97$ °C, one can forecast $<<T>>$ for the odd-even cycle pair of cycles 23–24; namely, $<<T>>_{23-24} = 9.99 \pm 0.29$ °C, this being the 90-percent prediction interval.

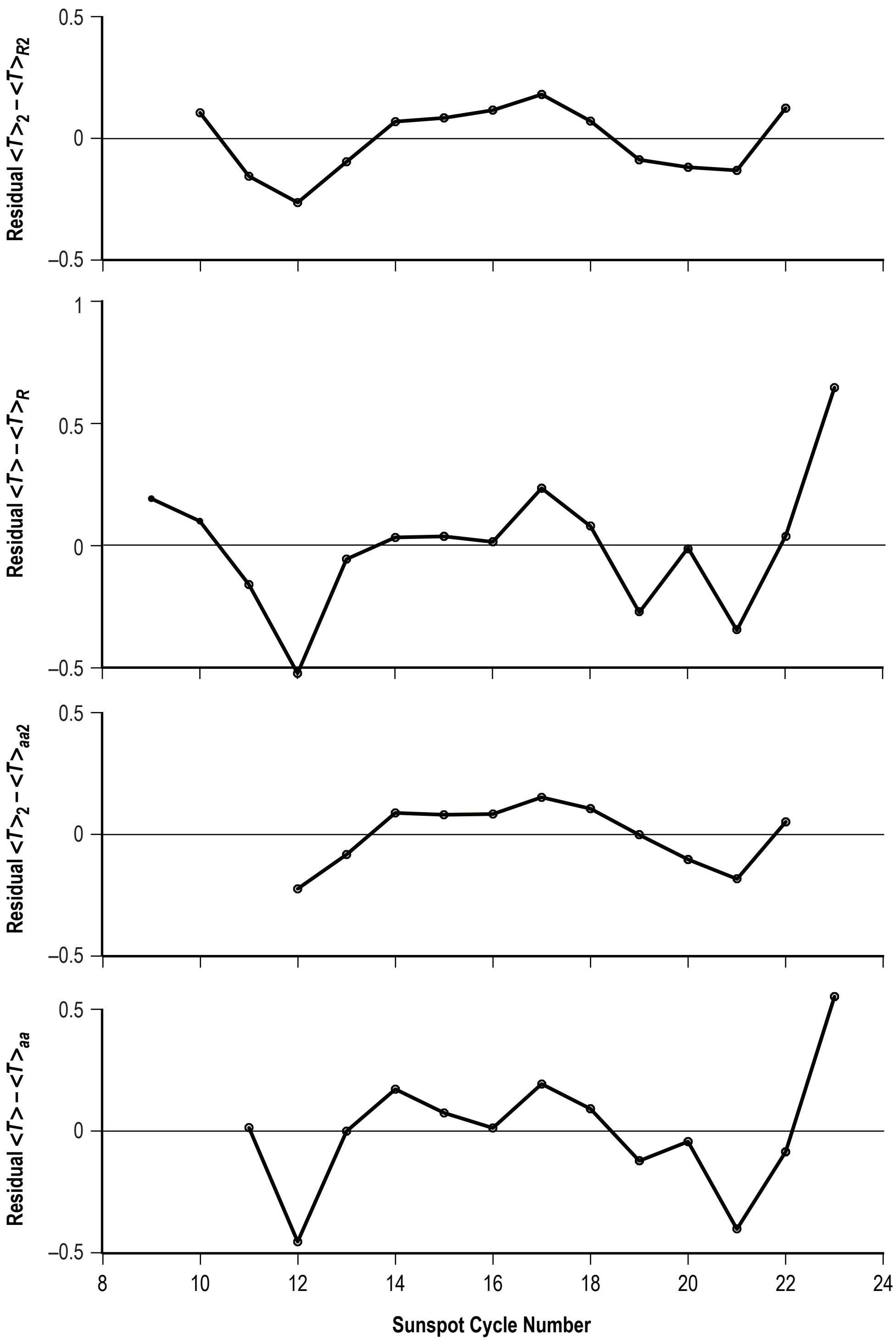

Figure 5. The residual $\langle T\rangle - \langle T\rangle_{aa}$ (lower panel), $\langle T\rangle_2 - \langle T\rangle_{aa2}$ (lower-middle panel), $\langle T\rangle - \langle T\rangle_R$ (upper-middle panel), and $\langle T\rangle_2 - \langle T\rangle_{R2}$ (upper panel), where $\langle T\rangle_{aa}$ is the regression fit for $\langle T\rangle$ versus $\langle aa\rangle$, $\langle T\rangle_{aa2}$ is the regression fit for $\langle T\rangle_2$ versus $\langle aa\rangle_2$, $\langle T\rangle_R$ is the regression fit for $\langle T\rangle$ versus $\langle R\rangle$ and $\langle T\rangle_{R2}$ is the regression fit for $\langle T\rangle_2$ versus $\langle R\rangle_2$. See text and nomenclature for details.

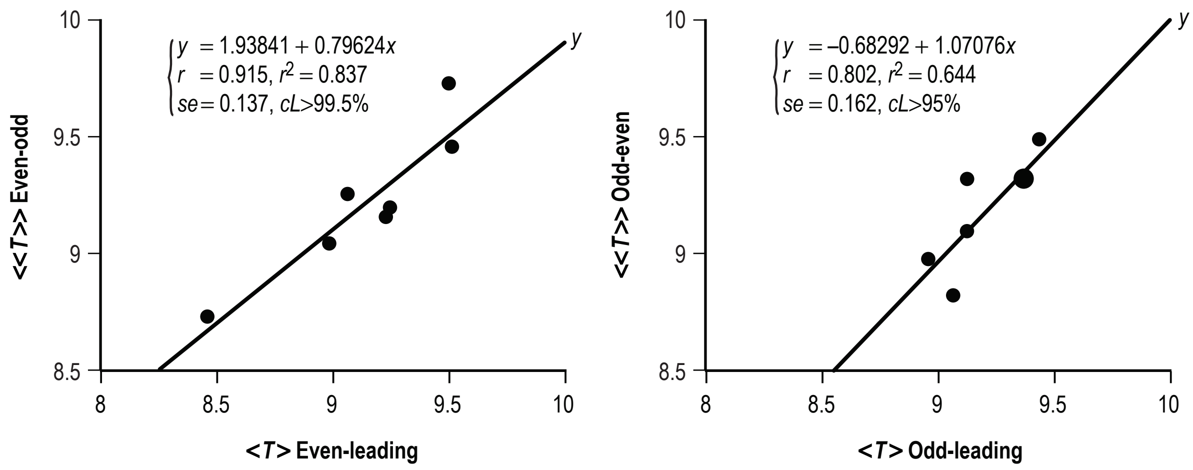

Figure 6. Scatterplots of average temperature for even-odd Hale cycle groupings versus temperature for the even-leading cycle (left panel) and temperature for odd-even Hale cycle groupings versus temperature for the odd-leading cycle (right panel). See text and nomenclature for details.

Figure 7 displays the variation of average temperature <<*T*>> (lower panel) over each Hale cycle even-odd cycle pair, where Hale cycle 1 is defined as sunspot cycles 10 + 11, Hale cycle 2 as sunspot cycles 12 + 13, and so forth. Also shown are the Hale cycle averages of the *aa*-geomagnetic index <<*aa*>> (middle panel) and sunspot number <<*R*>> (upper panel). Again, very strong resemblance is apparent between the parameters. For example, there is a dip in <<*T*>> for Hale cycle 2 (sunspot cycles 12 + 13), a local peak for Hale cycle 5 (sunspot cycles 18 + 19), another local dip for Hale cycle 6 (sunspot cycles 20 + 21) and a steep rise to Hale cycle 7 (sunspot cycles 22 + 23). For the current Hale cycle 7, <<*T*>> averages 9.72 °C, which is 1 °C higher than the minimum in Hale cycle 2 (8.72 °C) and which is the highest average of all the Hale cycles. (Recall, however, that the average temperature for Hale cycle 7 is really incomplete, because temperature data for the year 2005 has not yet been posted. Inclusion of the temperature for 2005, however, will not greatly affect the average temperature for Hale cycle 7.)

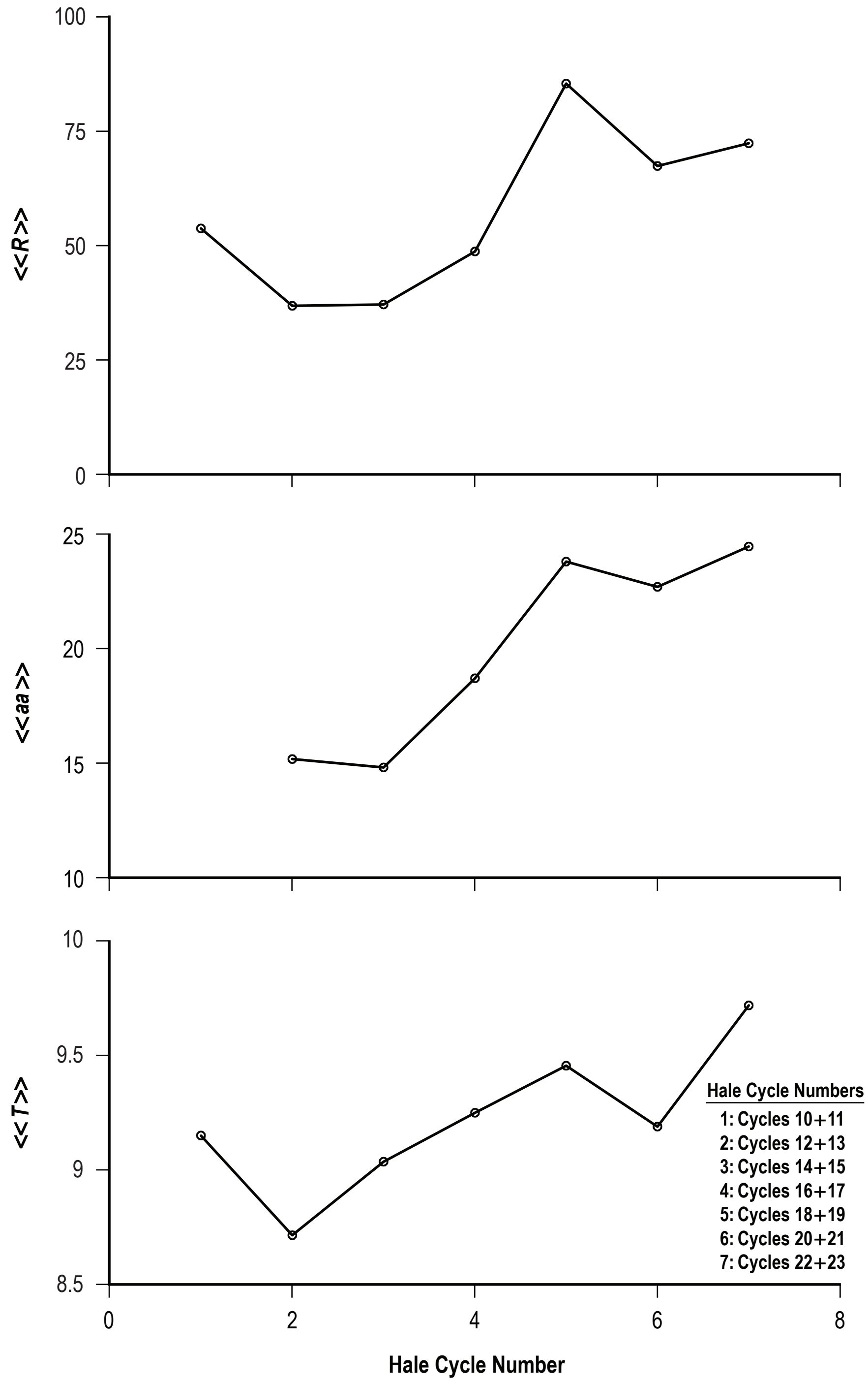

Figure 7. Cyclic variation of average temperature <<*T*>> (lower panel), the *aa*-geomagnetic index <<*aa*>> (middle panel) and sunspot number <<*R*>> (upper panel) for Hale cycles 1–7, using the preferred even-odd grouping of sunspot cycles. See text for details.

Figure 8 shows the scatterplots of <<*T*>> for each Hale cycle even-odd cycle pair versus <<*aa*>> (left panel), <<*R*>> (middle panel) and Hale cycle length in years (right panel). In all cases, the inferred regressions are statistically important. In particular, the inverse correlation between <<*T*>> and the length of the Hale cycle (associating higher temperature with shorter Hale cycle length) is quite strong (at the 0.2-percent level of significance, or 99.8-percent cl). The inverse correlation has r = –0.937, a coefficient of determination $r^2 = 0.877$ (this being a measure of the amount of variance explained by the inferred regression) and a standard error of estimate *se* = 0.115 °C. Previous studies have shown the importance of the length of the solar cycle—with respect to climate.[2,13–15] (Figure 8 has been drawn presuming that Hale cycle 7—cycles 22–23—will be 20 years in length, meaning that cycle 24 has its onset in the year 2006.[16,17] If Hale cycle 7 is longer than 20 years, this will weaken the correlation.)

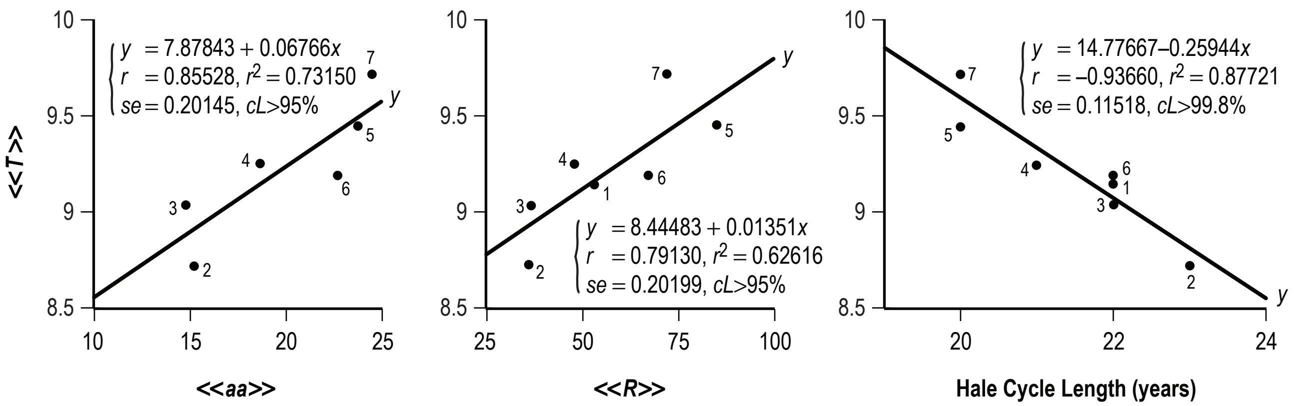

Figure 8. Scatterplots of <<*T*>> versus <<*aa*>> (left panel), <<*T*>> versus <<*R*>> (middle panel) and <<*T*>> versus Hale cycle length in years. See text and nomenclature for details.

3. CONCLUSION

Previously, Wilson[2] examined the Armagh Observatory temperature record for the interval 1844–1992. The purpose of the present study was to revisit that original study, updating the findings using the corrected and more extensive 1844–2004 temperature readings, which are now available online at <http://climate.arm.ac.uk/calibrated.html>.

The Armagh Observatory temperature record is one of the longest available for study. A prominent feature of long-term temperature studies has been a general warming since the 1880s. Because both sunspot number and the *aa*-geomagnetic index have shown similar secular increases, a strong association between trends in global temperature on Earth and trends in the solar/geomagnetic cycle should be apparent.

The *aa*-geomagnetic index was introduced in 1972 by Mayaud[18] to quantify fluctuations in the geomagnetic field, being based on pairs of near-antipodal magnetometers located in England and Australia. The record of the *aa*-geomagnetic index extends from 1868 to the present. Geomagnetic activity, as characterized using the *aa*-geomagnetic index, is caused by the solar wind, in particular, coronal mass ejections and high-speed streams from coronal holes and the associated changes of the interplanetary magnetic field, thereby, affecting the near-Earth interplanetary space.[19,20] Hence, the *aa*-geomagnetic index should be highly correlated with the sunspot cycle. In fact, as noted in the previous section, aa_{10} and R_{10} (the 10-year moving averages) are, indeed, highly correlated, having $r=0.933$. While true, the actual minimum annual value of the *aa*-geomagnetic index usually lags sunspot minimum (by one year[21]) and the maximum annual value almost always occurs during the declining phase of the sunspot cycle (only two exceptions—cycles 12 and 13; see fig. 1). Additionally, evidence exists that the *aa*-geomagnetic index can be decomposed into two components: one mimicking the sunspot cycle and the other (the residual) being indicative of recurrent high-speed streams in the solar wind.[22,23]

In this study, it has been shown that temperature at the Armagh Observatory averaged 9.215 °C during the interval 1844–2004, having a standard deviation of 0.521 °C and a median of 9.20 °C. Furthermore, annual mean temperatures at Armagh Observatory appear to vary systematically and nonrandomly, bearing a strong resemblance to the solar/geomagnetic cycle signatures as expressed using sunspot number and the *aa*-geomagnetic index (especially, the 10-year moving averages). The highest T occurred in 1846 (10.40 °C) and the lowest occurred in 1879 (7.40 °C), while the highest T_{10} occurred in 1999 (the last entry, 9.95 °C) and the lowest in 1883 (8.44 °C). Thus, from 1883 to 1999, T_{10} rose 1.51 °C, or about 0.013 °C per year. For 7 of the last 10 years of the temperature record, annual mean temperatures at Armagh Observatory exceeded 10 °C, an unprecedented occurrence in the record.

While there has been an overall rise (warming) in T_{10}, similar to rises in sunspot and geomagnetic activity, the residual of temperature (having removed the effect of solar/geomagnetic forcing) appears episodic, with intervals indicative of both cooling and warming. The current warming (through 1999) is found to exceed that which one expects based on solar/geomagnetic forcing by more than 2.6 standard deviations.[7]

Another way of illustrating temperature variation is the use of temperature averages over each solar cycle. Averaged in this way, temperature variations strongly mimic those of the solar/geomagnetic cycle. In particular, variations in 2-cycle moving averages of the parameters (a proxy for the Hale cycle—two successive sunspot cycles) are closely related, with $<T>_2$ being lowest in cycle 12 and highest in cycle 22 (although it will undoubtedly be exceeded in cycle 23). About 75 percent of the variance of $<T>_2$ can be explained by the variation in $<aa>_2$. Furthermore, there may be a 9-cycle variation embedded in the temperature record, as well (as in the sunspot record[11]).

Averages of temperature ($<<T>>$) over even-odd Hale cycle pairs, likewise, strongly associates with similar averages for the solar/geomagnetic cycle. Hale cycle 2 (sunspot cycles 12 + 13) has the lowest average temperature (8.72 °C) and Hale cycle 7 (sunspot cycles 22 + 23) has the highest temperature (9.72 °C). While $<<T>>$ correlates strongly against $<<aa>>$ and $<<R>>$, an even stronger inverse correlation ($r = –0.937$) is found between $<<T>>$ and the length of the Hale cycle, with higher average temperature being associated with shorter Hale cycle length. Indications are that the next Hale cycle will likely see even higher average temperature.

In conclusion, this study has shown that solar/geomagnetic cycle forcing is embedded in the annual mean temperatures at Armagh Observatory, Northern Ireland. Removal of this effect, however, does not fully explain, especially, the rapid rise in temperatures now being experienced, this possibly being a strong indication that humankind is contributing to climatic change.[24]

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13. ABSTRACT *(Maximum 200 words)*

The long-term annual mean temperature record (1844–2004) of the Armagh Observatory (Armagh, Northern Ireland, United Kingdom) is examined for evidence of systematic variation, in particular, as related to solar/geomagnetic forcing and secular variation. Indeed, both are apparent in the temperature record. Moving averages for 10 years of temperature are found to highly correlate against both 10-year moving averages of the *aa*-geomagnetic index and sunspot number, having correlation coefficients of ≈0.7, inferring that nearly half the variance in the 10-year moving average of temperature can be explained by solar/geomagnetic forcing. The residuals appear episodic in nature, with cooling seen in the 1880s and again near 1980. Seven of the last 10 years of the temperature record has exceeded 10 °C, unprecedented in the overall record. Variation of sunspot cyclic averages and 2-cycle moving averages of temperature strongly associate with similar averages for the solar/geomagnetic cycle, with the residuals displaying an apparent 9-cycle variation and a steep rise in temperature associated with cycle 23. Hale cycle averages of temperature for even-odd pairs of sunspot cycles correlate against similar averages for the solar/geomagnetic cycle and, especially, against the length of the Hale cycle. Indications are that annual mean temperature will likely exceed 10 °C over the next decade.

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