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Evidence for solar-cycle forcing and secular variation in the Armagh Observatory temperature record (1844-1992)

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Abstract. A prominent feature of previous long-term temperature studies has been the appearance of warming since the 1880s, this often being taken as evidence for anthropogenic-induced global warming. In this investigation, the long-term, annual, mean temperature record (1844-1992) of the Armagh Observatory (Armagh, North Ireland), a set of temperature data based on maximum and minimum thermometers that predates the 1880s and correlates well with northern hemispheric and global standards, is examined for evidence of systematic variation, in particular, as related to solar-cycle forcing and secular variation. Indeed, both appear to be embedded within the Armagh data. Removal of these effects, each contributing about 8% to the overall reduction in variance, yields residuals that are randomly distributed. Application of the 10-year moving average to the residuals, furthermore, strongly suggests that the behavior of the residuals is episodic, inferring that (for extended periods of time) temperatures at Armagh sometimes were warmer or cooler (than expected), while at other times they were stable. Comparison of cyclic averages of annual mean temperatures against the lengths of the associated Hale cycles (i.e., the length of two, sequentially numbered, even-odd sunspot cycle pairs) strongly suggests that the temperatures correlate inversely ($r = -0.886$ at <2% level of significance) against the length of the associated Hale cycle. Because sunspot cycle 22 ended in 1996, the present Hale cycle probably will be shorter than average, implying that temperatures at Armagh over this Hale cycle will be warmer (about 9.31 ± 0.23°C at the 90% confidence level) than average (= 9.00°C).

1. Introduction

The link between activity on the Sun and change in weather/climate on Earth has had a very storied past [e.g., *Green*, 1979; *Herman and Goldberg*, 1978; *Hines and Halevy*, 1977; *Lean et al.*, 1995; *Meadows*, 1975; *Molnar*, 1981; *Pittock*, 1978, 1983; *Reid*, 1991; *Schatten and Arking*, 1990; *Scherrer*, 1979; *Siscoe*, 1978; *Taylor*, 1986; *Tinsley et al.*, 1989; *Willett*, 1961], and the controversy surrounding this issue remains evident even today [e.g., *Crowley and Kim*, 1996; *Lastovicka*, 1996; *Pudovkin and Veretenenko*, 1995; *Hoyt and Schatten*, 1997; *Terez and Terez*, 1996; *Tinsley*, 1997; *Willson*, 1997]. In this investigation, the statistical aspects of the long-term (1844-1992), annual, mean temperature record of the Armagh Observatory (Armagh, North Ireland) are examined [cf. *Butler*, 1994; *Butler and Johnston*, 1994, 1996], specifically, as they may relate to solar-cycle forcing, secular variation, and the Hale cycle. Also, decadal average anomalies of the mean temperatures are compared against those of *Parker et al.* [1994], in order to determine the potential usefulness of the Armagh data as a monitor for northern hemispheric and/or global climatic change.

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2. Results and Discussion

2.1. The Armagh Observatory Temperature Record

Meteorological observations at Armagh Observatory (latitude 54°, 21.2′ N, longitude 6°, 38.9′ W) date from 1795, and except for the brief, 9-year interval of 1825 to 1833, the data are complete [*Butler*, 1994; *Butler and Johnston*, 1994, 1996]. Thus, the Armagh Observatory data span an interval that extends beyond the usual beginning point (~ 1880) for surface temperature studies [e.g., *Parker et al.*, 1994; *Hansen et al.*, 1996]. According to *Butler* [1994], the meteorological station is situated close to the center of the observatory grounds (a 20-acre site) on top of a "drumlin" at an altitude of 61 m above mean sea level. Measurement of the daily values of maximum and minimum temperatures at this site began in 1843, and the average of these two extremes defines the mean temperature record.

Butler and Johnston [1994, 1996] have given a number of reasons as to why the Armagh Observatory temperature record is of particular value, especially in a discussion of climatic change. For example, they note that (1) the mean temperature at Armagh has been found to correlate strongly with the northern hemispheric mean temperature record (1880-1985), as given by *Hansen and Lebedeff* [1987]; (2) the relatively small amplitude of the temperature variation in North Ireland (both diurnal and annual) implies a smaller statistical uncertainty in the mean temperature than for a more continental site; (3) the strong maritime climate of North Ireland implies that air

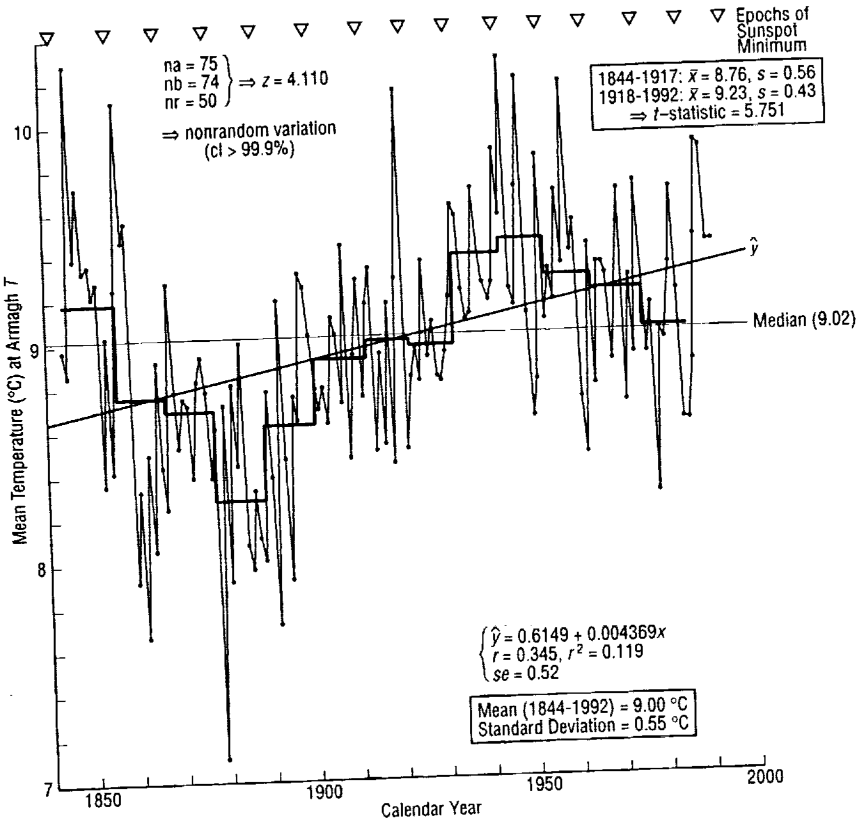

Figure 1. Annual mean temperature (°C) at Armagh Observatory during 1844-1992. The dotted jagged line represents the annual mean temperatures (T), the heavy horizontal lines represent cycle-length averages of the annual mean temperature, and the diagonal line moving from lower left to upper right represents the inferred long-term, linear secular increase in T. See text for additional details.

temperatures are coupled and moderated by Atlantic Ocean temperatures and therefore are more representative of a large region and less affected by local influences than many more continental stations; (4) few changes in the siting of the meteorological instruments have taken place; (5) the relatively small population size (being roughly constant at 8000 to 14,000 people since the early 19th century) and lack of urban encroachment suggest that microclimatic effects are minimal; and (6) the great interest in meteorology and longevity of Armagh Observatory's third director (1823-1882), T. R. Robinson, ensured a careful, conscientious, and systematic approach for the recording of temperature data.

Figure 1 displays the provisional annual mean temperature record (in degrees Celsius) at Armagh Observatory, denoted T, for the interval of 1844-1992, taken directly from *Butler* [1994]. Although the provisional temperatures incorporate all known corrections, as of 1994, the reader should note that the series is presently being reexamined by Butler and colleagues to ascertain whether or not any additional corrections may be necessary (e.g., due to potential second-order effects, like possible temperature-dependent thermometer errors in the early years, heat-island effects, and adjustment due to changes in the time of observation) in order to determine the final definitive record. Such corrections (if found) may ultimately cause a specific yearly value of mean temperature to slightly shift; however, these possible shifts are not expected to alter the main results of this investigation, which specifically are related to long-term trends embedded within the temperature series that strongly suggest the presence of solar-cycle forcing and secular variation (C. J. Butler, private communication, 1997).

In Figure 1, the annual means are easily recognized as the dotted jagged line that runs from left to right. For the interval of 1844-1992, annual mean temperature at Armagh Observatory has ranged between 7.11°C (1879) and 10.28°C (occurring twice: 1846 and1945). On average, the annual mean temperature has measured 9.00°C, having a standard deviation of 0.55°C. To find out whether or not the distribution of annual mean temperatures is randomly distributed, one performs a runs test [*Langley*, 1971, p. 322]. To do this, one simply counts the number (na) of years when the annual mean temperature is either equal to or above the median value of annual mean temperature (9.02°C), the number (nb) of years when it is below the median, and the number (nr) of runs or sequences that comprise the time series (these values are given near the top of Figure 1). The runs test yields a z statistic equal to 4.110, which indicates that the distribution of annual mean temperatures at Armagh Observatory, probably, is non-random (at <0.1% level of significance, or >99.9% level of confidence, cl). Similarly, dividing the sample into two subgroups of equal size results in the first subgroup (1844-1917) having a mean (standard deviation) equal to 8.76 (0.56)°C and the second subgroup (1918-1992) having a mean (standard deviation) equal to 9.23 (0.43)°C. On the basis of hypothesis testing of the difference of two means [*Lapin*, 1978, p. 486], one easily computes a t-statistic equal to 5.751,

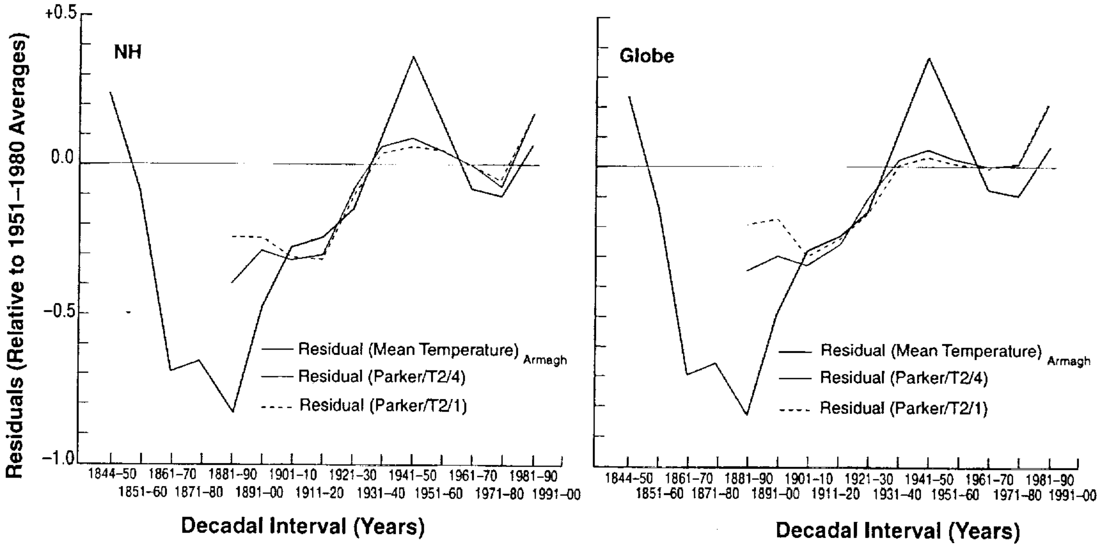

Figure 2. Comparisons of decadal averages of anomalies (against the means of 1951-1980) for the Armagh temperature data (the heavier line) and two sets determined by *Parker et al.* [1994] (based on coverage criteria) for the northern hemisphere (left) and globe (right).

inferring that the difference of the two sample means is statistically significant (at >99.9% cl). Therefore, one surmises that during the interval of 1844-1992, a shift to higher annual mean temperatures occurred. On the basis of linear regression analysis, one can describe this change in terms of a long-term linear increase of annual mean temperature, shown in Figure 1 as the diagonal line moving from lower left to upper right. The correlation of annual mean temperature against time (year) has a correlation coefficient $r = 0.345$, implying a coefficient of determination $r^2 = 0.119$ (i.e., the inferred regression can explain about 12% of the variance in T). The slope (0.004369) is found to be statistically significant (as compared to the null slope), implying that the inferred increase in T over time must be considered real.

Now, one could stop here and argue that, because the inferred secular increase in T over time, an increase of about 0.044°C per decade or about 0.44°C per century, coincides with the dramatic increase in the use of fossil fuels, it must be attributed solely to the influence of humans on climate (i.e., the anthropogenic effect); hence global warming has been apparent for some time, based on the temperature record, and plays the major role in long-term climatic change. However, to do so is sophomoric and obviously ignores the effects of other potentially associated climate-inducing factors, one such factor being the possibility of solar-cycle forcing.

Also shown in Figure 1 (across the top) are the epochs of sunspot minimum years that denote the conventional starts/ends of the solar cycle. The time span of 1844-1992 corresponds to solar cycles 9 through the declining portion of cycle 22 (actually, cycle 9 had its conventional start in 1843). Drawn as heavy horizontal lines of solar-cycle length are the average temperatures at Armagh Observatory for cycles 9-21. Clearly, one sees that cycle-length average temperature initially trended downward for several solar cycles before showing evidence of a substantial upward movement (also, for several solar cycles). Such behavior is quite reminiscent of the historical behavior of the solar cycle, in particular, as described using the proxies of sunspot number and the aa geomagnetic index [cf. *Cliver et al.*, 1996; *McKinnon*, 1987; *Wilson*, 1989]. Hence the annual mean temperature record at Armagh Observatory may have embedded within it a solar-cycle forcing term that must be evaluated and removed before concluding that all of the inferred secular rise can be attributed potentially to global warming, or some longer-term, natural climatic variation.

Before evaluating the degree of solar-cycle forcing that appears to be inherent within the Armagh mean temperature record, it may be instructive to compare the Armagh data against a "sanctioned" data set, such as the one given by *Parker et al.* [1994], to determine their degree of agreement (or lack of agreement). Providing that the behavior of the two data sets is similar (i.e., strongly correlated), one argues that the Armagh mean temperature series might provide additional insight into the mechanisms of climatic change and, in particular, might be able to elucidate on the behavior of temperature trends, especially prior to 1880, the general beginning for long-term temperature studies.

Recall that *Parker et al.* [1994] have presented global fields and tabulations of decadal annual surface temperature anomalies (referred to the mean of 1951-1980) for each decade from 1881-1890 through 1981-1990, in terms of each hemisphere and for the globe. Their results essentially confirmed the earlier works of *Jones* [1988], *Jones and Briffa* [1992], *Jones and Kelly* [1983], *Jones et al.* [1986a, b], *Hansen and Lebedeff* [1987, 1988], etc., and in fact, extended those published by the Intergovernmental Panel on Climate Change [cf. *Folland et al.*, 1990, 1992].

Figure 2 displays decadal averages of the residual of Armagh mean temperatures (as the heavy line), with respect to its 1951-1980 average (= 9.17°C), and of those taken from *Parker et al.* [1994], which represent particular area-weighted averages using Meteorological Office Historical Sea Surface Temperature (MOHSST) data, both for the northern hemisphere (left) and the globe (right). In particular, the thin lines refer to the anomalies computed from decadal anomaly fields using the same averaging technique, but ones that are based on a stricter coverage criteria for the input data, as compared to the dashed lines (see Parker et al. for details). (Specifically, the thin lines

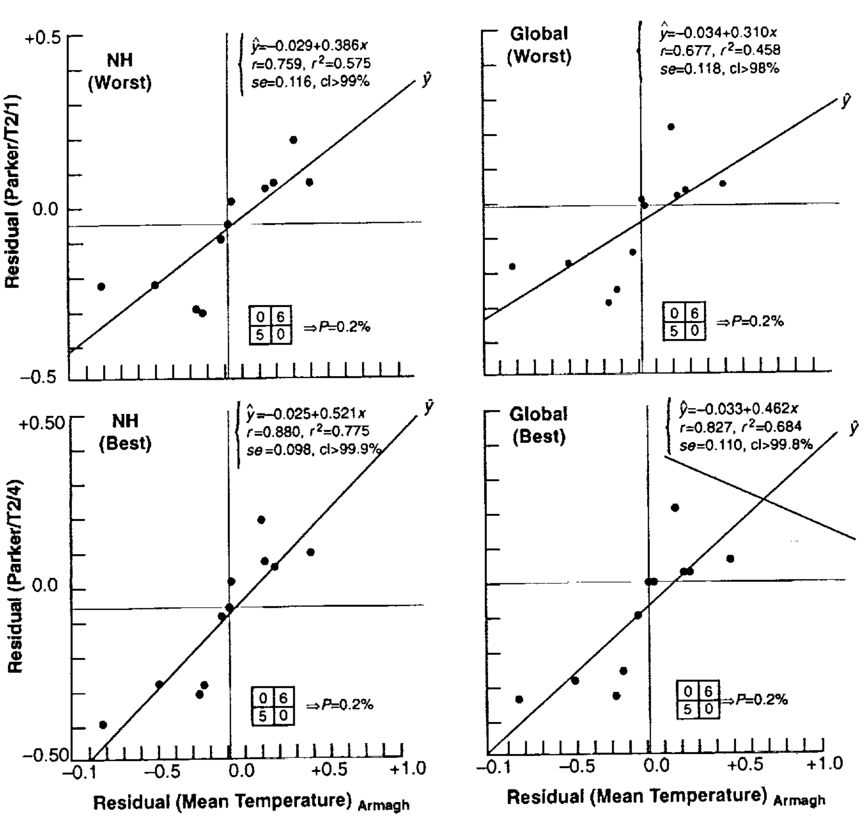

Figure 3. Scatterplots of decadal averages of anomalies, comparing the *Parker et al.* [1994] values against the Armagh values. The ones using the stricter coverage criteria are plotted in the lower panels (and are denoted "best"); the ones for the northern hemisphere are plotted in the left panels; and the ones for the globe are plotted in the right panels.

represent the set of decadal averages taken from Parker et al.'s Table 2, column 4, page 14,391, while the dashed lines represent the set of decadal averages taken from the same table, but now column 1.)

From Figure 2, one finds that the separate behaviors (i.e., their trends) of the Armagh and MOHSST anomalies agree remarkably well. For example, comparing the heavy (Armagh) and thin lines (the strictest values), whether the comparison is based on just northern hemispheric readings or on global values, one finds that both data sets show the 1880s to be the greatest in negative value (i.e., the coolest), with the anomalies decreasing in size (i.e., shrinking toward zero) with the passage of time, becoming positive in value in the 1930s. Likewise, both data sets show a local peak in the 1940s, a local dip in the 1960s and 1970s, and a rise to warmer temperatures in the 1980s. While, quantitatively, the sizes of the peaks and dips (extremes) have been somewhat larger as reckoned from the Armagh data, the general qualitative agreement of the two data sets suggests that they will be well-correlated, especially, if the comparison is based upon a linear regression analysis.

Figure 3 displays the scatter plots for the two cases of northern hemispheric (left panels) and global (right panels) anomalies, each, separately, for the two different subcases based on coverage (column 4, stricter coverage, bottom panels; column 1, top panels). Within each subpanel, the thin vertical and horizontal lines refer to the observed median values, so that Fisher's exact test [e.g., *Everitt*, 1977, p. 15] can be performed. The results of such an analysis appear beside the depicted 2x2 contingency tables; namely, for each case the probability of obtaining the observed result, or one more suggestive of a departure from independence (chance), is computed to be $P = 0.2\%$, inferring that when the Armagh anomaly is greater (or less) than its median value, the MOHSST anomaly, likewise, is greater (or less) than its median value. On the basis of a linear regression analysis, the Armagh and MOHSST anomalies, indeed, appear to be well-correlated, having $r \geq 0.76$ when the comparison is against the northern hemispheric anomalies (at >99% cl) and $r \geq 0.68$ when the comparison is against the global anomalies (at >98% cl). The strongest correlations result when the comparisons use the stricter (column 4) coverage data, having $r = 0.88$ for the northern hemispheric readings (at >99.9% cl) and $r = 0.83$ for the global readings (at >99.8% cl). The importance of this finding is that it strongly suggests that the Armagh annual mean temperature record can be used successfully to infer trends indicative of climatic change, both for the northern hemisphere and the globe. More interestingly, it expands the database to years prior to 1880, thus allowing for an assessment of the impact of climatic change based on a longer time frame of surface temperatures.

2.2. The Corresponding Solar-Cycle Record (1844-1992)

Figure 4 displays the records of annual sunspot number (bottom) and the aa geomagnetic index (top) for the years 1844-1992. Sunspot number is the most often used proxy for

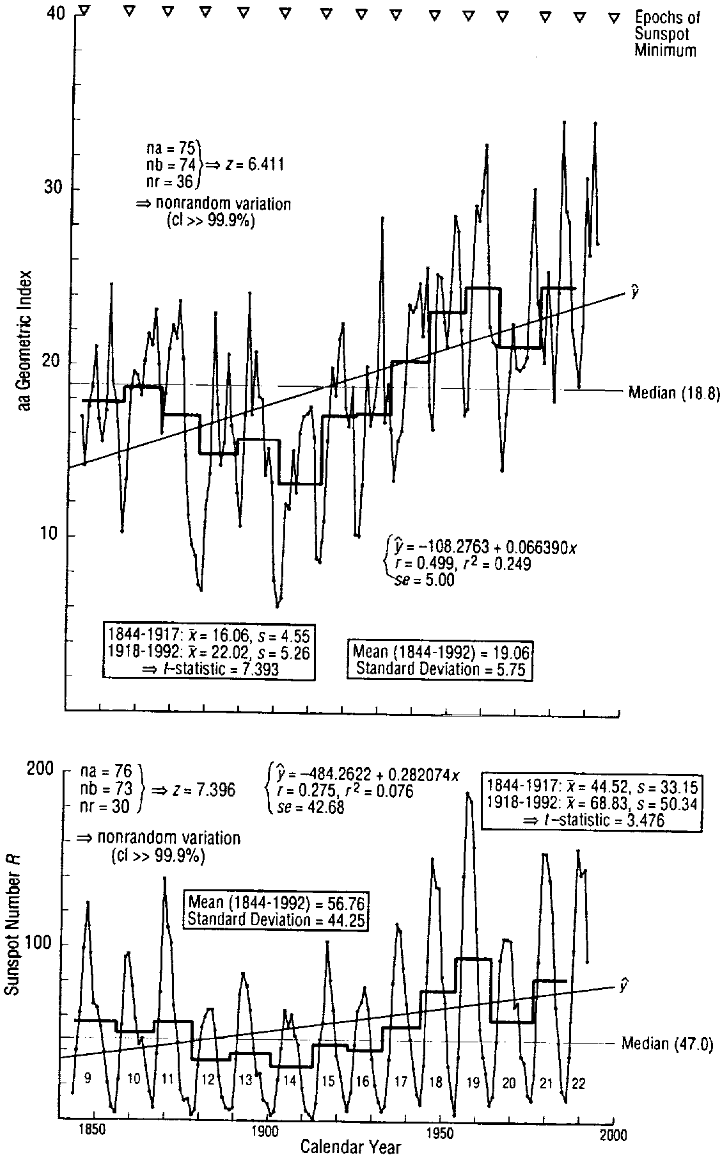

Figure 4. Annual values of solar cycle proxies during 1844-1992. (top) Annual values of the aa geomagnetic index. (bottom) Annual values of sunspot number *R*. The subpanels are drawn in similar fashion to that of annual mean temperature (Figure 1).

the solar cycle, owing chiefly to its relatively long observational record. Recall that Rudolf Wolf first introduced the so-called "sunspot-relative-number" in 1848, extending it back in time (in terms of yearly averages) to 1700 [*Waldmeier*, 1961; *McKinnon*, 1987; *Hoyt and Schatten*, 1997; *Schröder*, 1997]. Based on the completeness of the daily sunspot record, the inherent quality (i.e., reliability) of the data is considered "good" from 1849 to the present, "fair" from 1818 to 1848, and "poor" prior to 1818.

Similarly, the aa geomagnetic index provides an alternate proxy for the solar cycle, being nearly as long as the reliable portion of sunspot numbers (and in comparison to the length of the mean temperature record of the Armagh Observatory). Originally, the aa geomagnetic index was compiled by *Mayaud* [1973; cf. *Mayaud and Romana*, 1977] from hand-scaled K-values from two, almost antipodal, observatories in England and Australia, dating back to 1868; however, more recently, *Nevanlinna and Kataja* [1993], on the basis of hourly declination readings of the Helsinki magnetic-meteorological observatory, have extended the aa geomagnetic record back to 1844. (Many studies have shown the usefulness of the aa geomagnetic index for analyzing long-term trends in geomagnetic activity and as a proxy for studying secular changes in solar activity [e.g., *Borello-Filisetti et al.*, 1992; *Cliver et al.*, 1996; *Feynman*, 1982; *Kane*, 1997; *Legrand and Simon*, 1987, 1991; *Simon and Legrand*, 1989; *Thompson*, 1993; *Wilson*, 1990; *Wilson et al.*, 1998].)

Both sunspot number and the aa index should be examined as proxies for the solar-cycle forcing term because, while their cycle-to-cycle behavior is extremely well-correlated (on the basis of cyclic averages), their yearly values are somewhat less correlated with each other. For example, while sunspot number usually has a single, well-defined maximum for each cycle (occasionally, two main peaks, with one usually being the

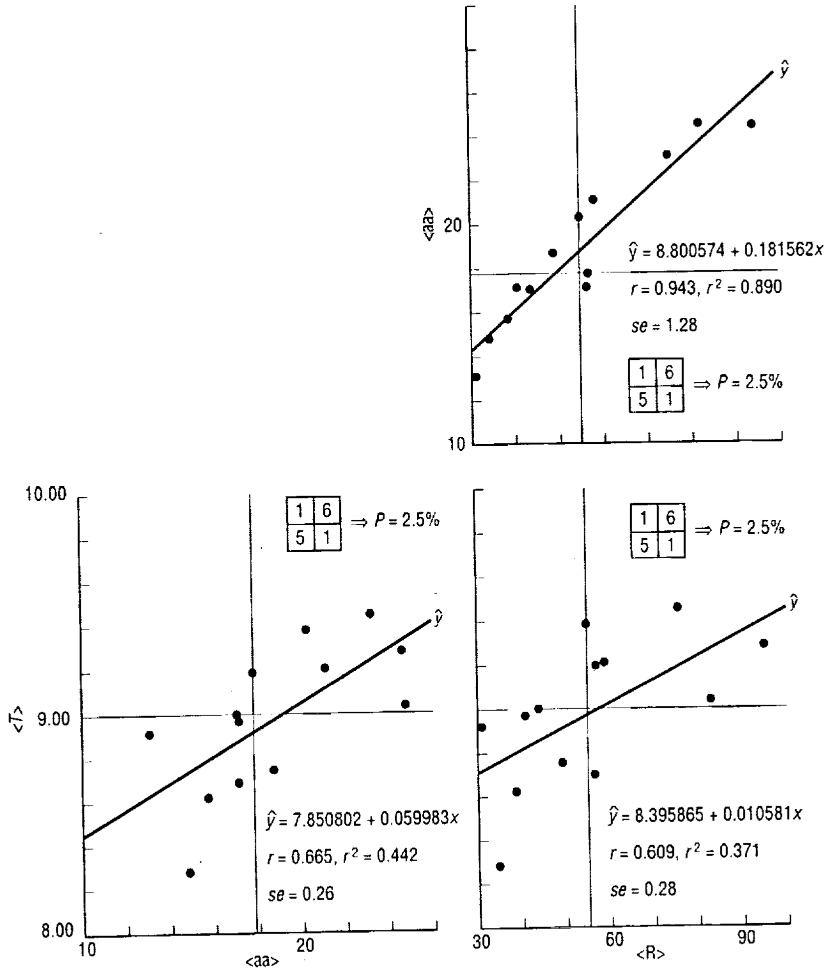

Figure 5. Scatter plots of cycle-length averages for selected combinations of parameters. (lower left) <*T*> versus <aa>. (lower right) <*T*> versus <*R*>. (upper right) <aa> versus <*R*>. In each subpanel, the results of Fisher's exact test for the observed 2x2 contingency table (determined by the medians, shown as the faint horizontal and vertical lines), or one more suggestive of a departure from independence (chance), is given as a probability *P*. The heavy diagonals are the inferred regression lines.

more dominant), the aa index generally has two or more peaks during each cycle (typically, with one being associated with the rising portion of the cycle and the other(s) being associated with the declining portion of the cycle). Also, the minimum value for the aa index, more often than not, follows sunspot minimum (i.e., it usually occurs during the year following sunspot minimum), and the maximum value for the aa index usually follows sunspot maximum (by 2 or more years). These behavioral differences may prove important in understanding the solar-cycle forcing that may be present in the annual mean temperatures as recorded at the Armagh Observatory.

For both data sets (i.e., sunspot number and the aa index), identical analyses were performed that were performed on the temperature data set. These include the runs test, hypothesis testing of the difference of two means, and linear regression analysis. As with the temperature data, both sunspot number and the aa index show nonrandom variation, with the more recent data of higher average value than the earlier data and with both showing a long-term, linear secular increase. Because of these strong similarities, one infers that the annual mean temperature record, very probably, contains at least, some small measure of solar-cycle forcing.

On the basis of cyclic averages for the individual data sets, Figure 5 depicts the inferred relationships between temperature <*T*> and the aa index <aa> (bottom left), <*T*> and sunspot number <*R*> (bottom right), and <aa> and <*R*> (top right). Of the two parameters that are representative of solar-cycle forcing, the one that relates strongest to temperature appears to be the aa index, which is found to explain about 44% of the variance in <*T*>. A bivariate analysis (not shown) results in the relationship being described as <*T*> = 7.745726 - 0.002836 <*R*> + 0.073888 <aa>, having a correlation coefficient equal to 0.63, a coefficient of determination equal to 0.40, and a standard error of estimate equal to 0.27°C.

2.3. Detrending the Armagh Observatory Temperature Record

From Figures 1 and 4, a linear regression analysis (not shown) of *T* versus *R* reveals that the two parameters are correlated (at >99.5% cl, having $r = 0.243$ and a standard error

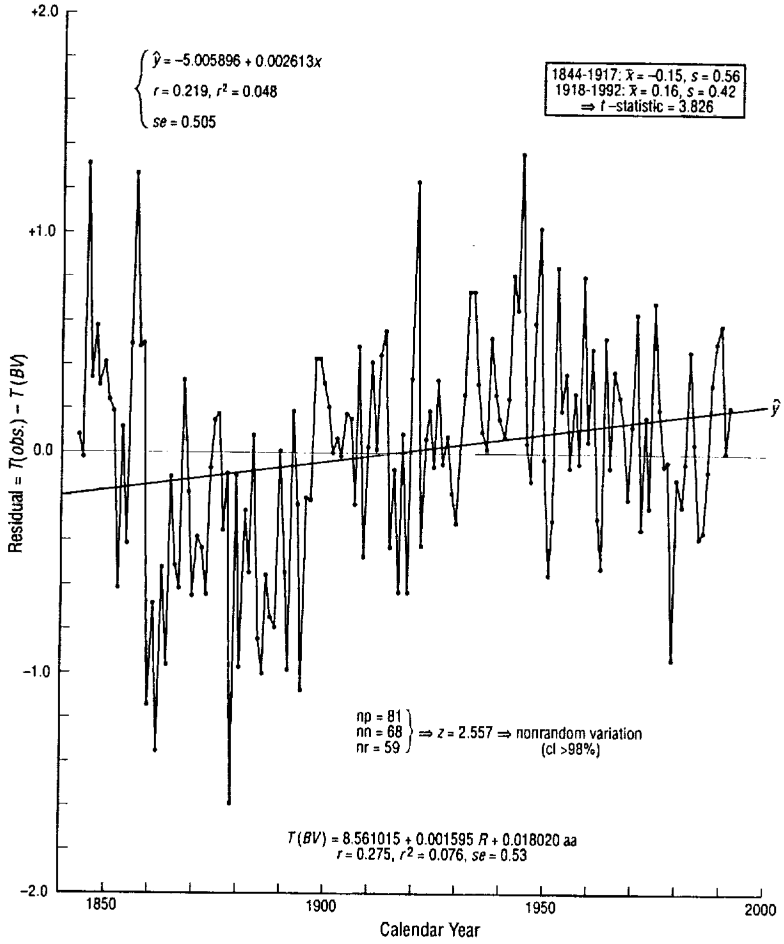

Figure 6. The detrended residual of annual mean temperature, having removed solar-cycle forcing. T(BV) refers to a bivariate fit of T versus R and aa. The diagonal line identifies the inferred long-term, linear secular increase in the residual of T that remains after detrending.

of 0.53°C). Likewise, a linear regression analysis (not shown) of T versus aa reveals that the two parameters are correlated (at >99.9% cl, having $r = 0.267$ and a standard error of 0.53°C). A bivariate analysis results in the regression $T(\mathrm{BV}) = 8.561015 + 0.001595\ R + 0.018020\ \mathrm{aa}$, having $r = 0.275$ (inferring that solar-cycle forcing can possibly account for about 8% of the variance in T) and a standard error of 0.53°C. Removing the solar-cycle forcing from the temperature series results in Figure 6, which displays the residual of T(Obs.) - T(BV).

A runs test of the residual shows that it, very probably (at >98% cl), still has embedded within it a non-random variation. Additionally, hypothesis testing of the difference of two means suggests that the more recently occurring residuals have tended to be positive in value, while the earlier occurring residuals tended to be negative in value. Thus the temporal behavior of the residuals is consistent with a statistically significant increase in the observed temperature over and above that which can be explained by simple solar-cycle forcing. A linear regression analysis of the residuals against time (year) also appears in Figure 6 (as the diagonal line running from lower left to upper right). This striking feature (i.e., a long-term, linear warming trend) is consistent with the results of *Kane and Teixeira* [1990], who performed a maximum entropy spectral analysis of annual mean surface temperature series for land masses and sea in the northern and southern hemispheres, although the slope is only about half the size of that reported by them.

Figure 7 pictures the residual of T(Obs.) - T(BV) - T(S), where T(S) is the inferred linear secular increase, given by the regression equation in Figure 6. A runs test of the resultant residuals suggests that they vary randomly ($z = 1.586$), and hypothesis testing of the difference of two means, likewise, suggests that it is not statistically important ($t = 1.468$). Thus the resultant detrended residuals, shown in Figure 7, are consistent with a random, non-systematic variation. Because one can use moving averages to reduce the effect of random variation in time series data [e.g., *Longley-Cook*, 1970, p. 175], the 10-year moving average (also called the 11-year running mean) is shown to identify the long-term episodic nature of the temperature variation. Thus, prior to about 1860, the annual mean temperature at Armagh (and, apparently, for the northern hemisphere and globe) is perceived to have been warmer than expected, while being cooler than expected from about 1860 to near 1900; annual mean temperature is perceived to have been stable (i.e., in general agreement with expectation) for the intervals of near 1900 until the mid-1920s and near 1950 until about 1970, while being warmer between about the mid 1920s and near 1950 and cooler between about 1970 and the end of

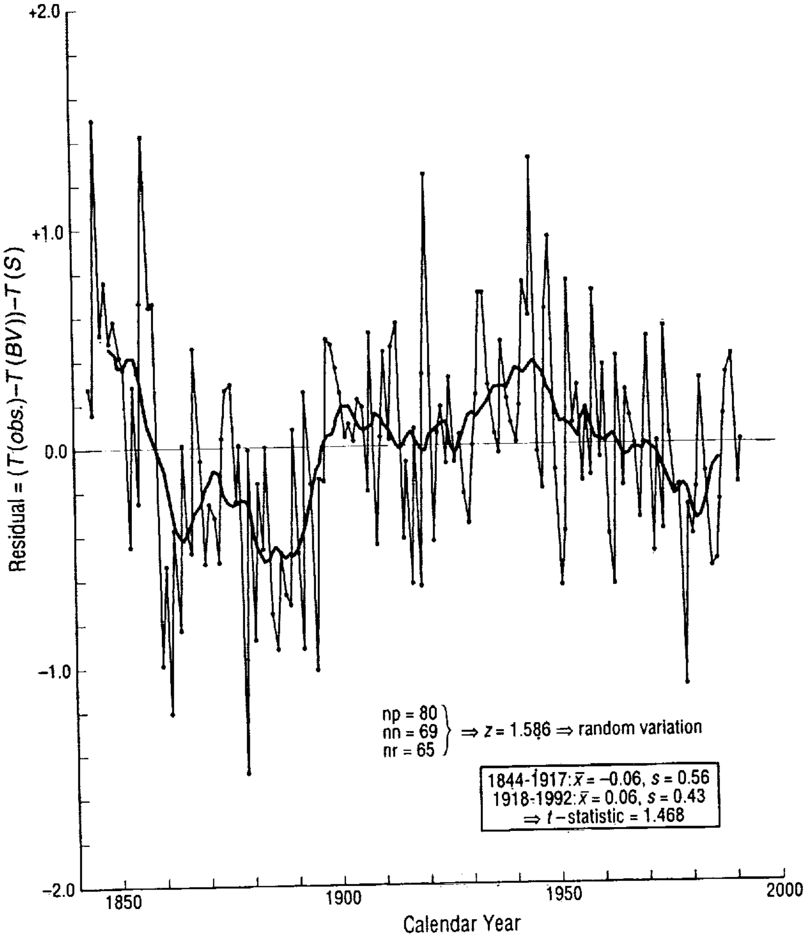

Figure 7. The detrended residual of annual mean temperature, having removed both solar- cycle forcing (*T*(BV)) and the inferred long-term, linear secular increase (*T*(S)). The dotted jagged line is the remaining residual in temperature, and the heavy smoothed line is the 10-year moving average. When the residual is of positive value, this refers to periods of warmer than expected *T*, and when the residual is of negative value, this refers to periods of cooler than expected *T*.

the record (although the trend has been towards warmer temperatures since about 1980).

2.4. The Hale Cycle Effect

While individual solar cycles have minima in activity, on average, every 11 years (i.e., the familiar sunspot cycle length, although it appears to be better described using a bimodal distribution [e.g., *Wilson*, 1987, 1988, 1993; *Wilson et al.*, 1996a]), the length of the cycle is really envisioned to be twice that length when one includes the behavior of the Sun's hemispheric magnetic polarity reversals. For example, during even-numbered sunspot cycles, the preceding spots of the Sun's northern hemisphere are predominantly of southward or negative polarity, while they are predominantly of northward or positive polarity during odd-numbered sunspot cycles. The behavior is opposite this for the Sun's southern hemisphere. This is referred to as the Hale cycle, named in honor of George Ellery Hale, who first studied this phenomenon [*Bray and Loughhead*, 1964; *Hale and Nicholson*, 1938; *Howard*, 1977].

The preferred pairing of individual sunspot cycles as a single Hale cycle is even-odd, in that order (i.e., each Hale cycle consists of an even-numbered leading cycle and odd-numbered following cycle). This even-odd pairing of sunspot cycles was first suggested by *Gnevyshev and Ohl* [1948] on the basis of the inferred strengths of correlations between ΣR for the even cycles and ΣR for both the odd-following and odd-preceding cycles [cf. *Kopecky*, 1991; *Vitinskii*, 1965; *Wilson*, 1992]. Thus cycles 10-11 represent a single Hale cycle, cycles 12-13 another Hale cycle, and so on, with the present Hale cycle pairing being cycles 22-23.

Figure 8 plots (in the left panels) Hale cycle averages of the Armagh annual mean temperature (<<*T*>>; upper left), the aa geomagnetic index (<<aa>>; middle left), and sunspot number (<<*R*>>; lower left) as a function of Hale cycle number, where Hale cycle 1 has arbitrarily been assigned to cycles 10-11. Plotted to the right of each is a scatter plot of <<*T*>>, <<aa>>, and <<*R*>> versus the individual Hale cycle length (which has measured 20, 21, 22, and 23 years). Perhaps, surprisingly, is the realization that the temporal behavior of <<*T*>> very closely resembles both that of <<aa>> and <<*R*>>, with all the parameters having a maximum in Hale cycle 5, corresponding

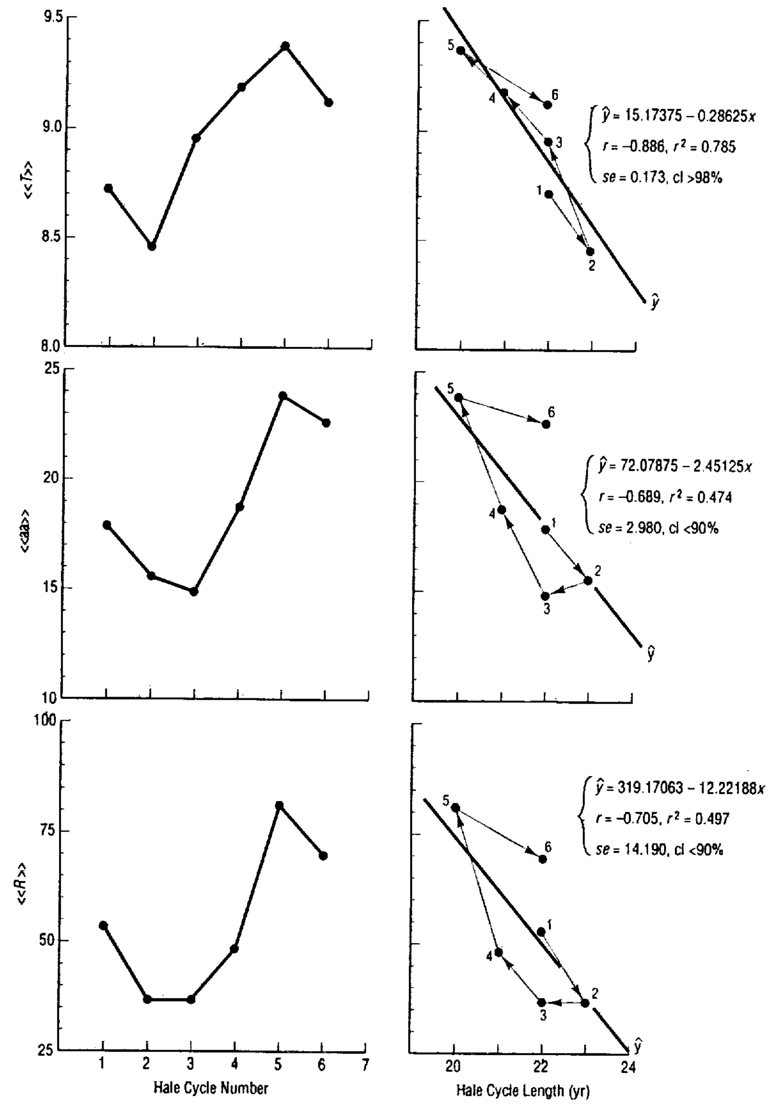

Figure 8. Hale cycle averages. (bottom left) <<*R*>> versus Hale cycle number. (middle left) <<aa>versus Hale cycle number. (top left) <<*T*>> versus Hale cycle number. (bottom right) <<*R*>> versus Hale cycle length. (middle right) <<aa>> versus Hale cycle length. (top right) <<*T*>> versus Hale cycle length.

to cycles 18-19. Perhaps, more surprisingly, is the realization that a very strong, linear inverse correlation appears to exist between <<*T*>> and the length of the Hale cycle ($r = -0.886$ at >98% cl), in contrast to that of <<aa>> and <<*R*>>, which seem to behave following a more circular pattern (a hysteresis-type behavior) than that of a strict linear inverse relationship. Thus, given the length of the Hale cycle, it appears that one can easily compute the average annual mean temperature at Armagh for the duration of that particular Hale cycle. As an example, if the present Hale cycle (number 7: cycles 22-23) has a length equal to 22 years (the average length), then one anticipates that <<*T*>> will be about 8.88 ± 0.37°C (at the 90% cl). On the other hand, if its length is shorter (longer) than the average length, then the inferred average temperature will be greater (less). A length of 21 years implies <<*T*>> = 9.16 ± 0.37°C, whereas a length of 20 years implies <<*T*>> = 9.45 ± 0.37°C. (It should be noted that, previously, *Friis-Christensen and Lassen* [1991] and *Butler and Johnston* [1996], respectively, found the variation of individual sunspot cycle length to be related to long-term variations of the northern hemispheric land air temperature and Armagh mean temperature.)

Figure 9 displays scatter plots of <<*T*>> versus <<aa>> (lower left), <<*T*>> versus <<*R*>> (lower right), and <<aa>> versus <<*R*>> (upper right). While a rather strong correlation exists between <<aa>>and <<*R*>>, as expected, one finds only a marginally significant one between <<*T*>> and, in particular, <<aa>> which undoubtedly, is due to the small sample size (only six Hale cycles). Still, one does expect <<*T*>> to increase as <<*R*>> and <<aa>> increase, as it does based solely on single cycle averages or annual values. Because <*R*> and <aa> are known for cycle 22, the even-leading component of the present Hale cycle, one might be able to use this information to better estimate the size and strength of the odd-following component, cycle 23, both in terms of <*R*> and <aa>, thereby yielding an estimate for the whole of Hale cycle 7.

Figure 10 depicts the scatter plots of <*R*> odd-following and <<*R*>> versus <*R*> even-leading (lower and upper left, respectively) and <aa> odd-following and <<aa>> versus <aa>

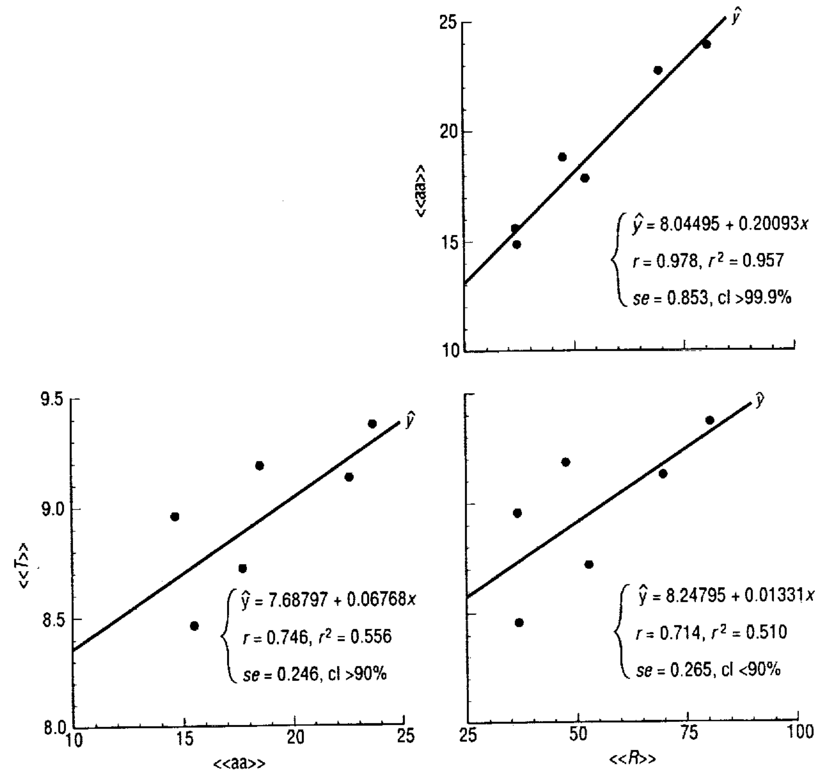

Figure 9. Scatter plots of Hale cycle averages. (bottom left) <<*T*>> versus <<aa>>. (bottom right) <<*T*>> versus <<*R*>>. (top right) <<aa>> versus <<*R*>>.

even-leading (lower and upper right, respectively). In all cases, knowledge of either <*R*> even-leading or <aa> even-leading is found to yield estimates of <*R*> odd-following and <aa> odd-following that are statistically meaningful. Thus there appears to be strong evidence for an even-odd cycle effect within both the sunspot record and the aa geomagnetic index record, one that cannot be denied [cf. *Wilson*, 1992; *Wilson et al.*, 1996b, d].

Given that <*R*> even-leading for cycle 22 equals 78.52 (based on the average *R* for the years 1986-1995; i.e., accepting cycle 23 onset, on the basis of annual sunspot number, in 1996), one infers that <*R*> odd-following (cycle 23) should be about 100.6 ± 13.7 and that <<*R*>> for Hale cycle 7 (the present Hale cycle) should be about 86.1 ± 7.0 (at the 90% cl). Also, given that <aa> (for cycle 22) equals 25.84, one infers that <aa> (for cycle 23) should be about 26.9 ± 5.0 and that <<aa>> for Hale cycle 7 should be about 26.3 ± 2.3 (at the 90% cl). Applying the derived values of <<*R*>> and <<aa>> for Hale cycle 7 to the regression equations identified in Figure 10 yields <<*T*>> = 9.39 ± 0.57°C (based on <<*R*>>) and <<*T*>> = 9.47 ± 0.52°C (based on <<aa>>), both values consistent with the idea that Hale cycle 7 will be shorter than average.

Figure 11 pictures <*T*> odd-following versus <*T*> even-leading (bottom) and <<*T*>> versus <*T*> even-leading (top). The even-odd effect that dominates the sunspot and aa geomagnetic index records also is evident in the mean temperature record. Therefore, given the <*T*> even-leading value (for cycle 22) allows one to better predict both <*T*> odd-following (for cycle 23) and <<*T*>> (for Hale cycle 7). A. Coughlin (private communication, 1997) has kindly provided the unpublished monthly mean temperatures at Armagh Observatory for the years 1993-1996, which can easily be averaged to yield annual mean temperatures, *T*, for 1993-1996 and to yield <*T*> for cycle 22. These values are 9.16, 9.32, 9.61, 8.98, and 9.36°C. Using <*T*> (for cycle 22) = 9.36°C, one infers that <*T*> (cycle 23) should be about 9.24 ± 0.47°C and that <<*T*>> (Hale cycle 7) should be about 9.31 ± 0.23°C (this latter value providing further indication that Hale cycle 7 will be shorter and warmer than average).

3. Summary and Concluding Remarks

Separating natural and human-induced effects as related to climatic change, especially long-term aspects, are essential to properly describe and understand Earth's climatic system. One measure of climatic change is the behavior of temperature fluctuations (differentiating those that are systematic from those that are nonsystematic). One of the longest time series of continuous temperature records in existence is the one of annual mean temperature (based on maximum and minimum thermometers) recorded at Armagh Observatory in Armagh, North Ireland which dates back to 1844, spanning an interval that is commensurate with both sunspot number and the aa geomagnetic index, two often used proxies for the solar cycle.

Examining only the temperature record itself (i.e., ignoring solar-cycle forcing) has revealed that embedded within it is a long-term, linear increase against time, implying that annual mean temperature has increased systematically (about 0.044°C per decade or about 0.44°C per century) over, at least, the past 150 years. Such a finding, however, is not new, having been

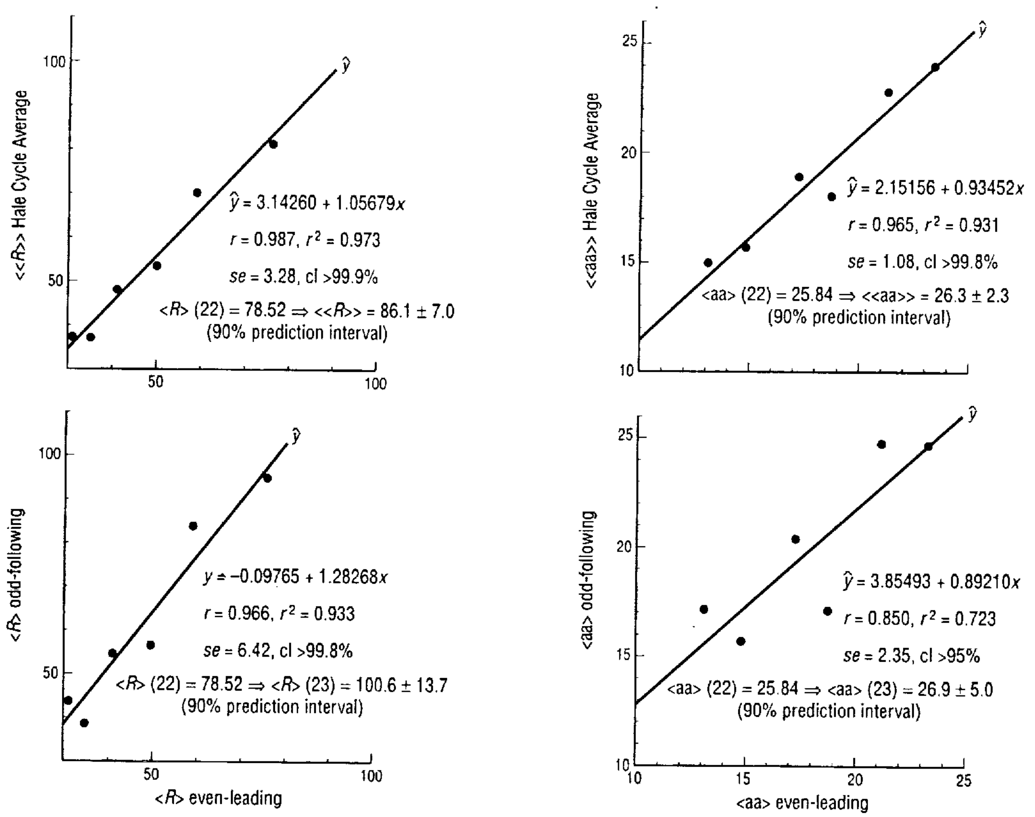

Figure 10. The even-odd cycle effect in *R* and aa; (bottom left) <*R*>odd-following cycle average versus <*R*>even-leading cycle average; (top left) <<*R*>> Hale cycle average versus <*R*>even-leading cycle average; (bottom right) <aa> odd- following cycle average versus <aa>even-leading average; (top right) <<aa>> Hale cycle average versus <aa>even-leading cycle average.

shown in a number of temperature data sets of shorter length [cf. *Kane and Teixeira*, 1990; *Hansen et al.*, 1996]. Often, this inferred linear increase in temperature has been interpreted as evidence for global warming, in particular, for anthropogenic-induced global warming [cf. *Kane and de Paula*, 1996]. However, because solar-cycle length averages of temperature variation bear a strong resemblance to the behavior of both sunspot number and the aa geomagnetic index, proxies of the solar cycle, a compelling case linking, at least, some of the variation in temperature to solar-cycle forcing is evident. Consequently, before one can truly interpret the inferred rise in temperature (i.e., global warming) that has been found in the annual mean temperature as being due entirely to the effects of greenhouse gases (such as, CO_2), one must first determine the degree of solar-cycle forcing that is present.

This investigation has shown that, at least, some of the variation in the annual mean temperature as recorded at the Armagh Observatory during the interval of 1844-1992 can be attributed directly to solar-cycle forcing (about 8% of the variance can be explained as a consequence of the action of the solar cycle). Removal of this solar-cycle forcing term yields residuals that still show the presence of a long-term, linear secular increase, albeit one that is now only about half the size as originally suggested. Together, solar-cycle forcing and the long-term, linear secular increase can explain about 16% of the variance in the Armagh annual mean temperature record of 1844-1992. The distribution of residuals, having removed the solar-cycle forcing and long-term, linear secular increase, appears to be distributed randomly, so the remaining variation must be considered as being due to noise and/or natural fluctuation. (It must be emphasized that this study has investigated only the long-term aspects of climatic change, in particular, as suggested in the *Butler* [1994] Armagh annual mean temperature record. A second study concerning possible short-term effects, such as those that might result from the occurrences of catastrophic volcanic eruptions [e.g., *Hansen et al.*, 1997; *Robock and Mao*, 1995] or El Niño [e.g., *Enfield and Mayer*, 1997], may follow.)

Analysis of the remaining residuals, using the 10-year moving average, has shown that for extended periods of time the residual was predominantly either warmer, cooler, or stable as compared to that which was expected for it (based on the amount of solar-cycle forcing and secular variation that occurred). Most recently, the residuals have trended toward more positive (warmer) value (beginning in 1982, having been cooler than expected since 1971).

Although the published data end in 1992, recordings of mean temperature at Armagh continue on a daily basis today and, hopefully, will continue for the foreseeable future. For cycle 22, annual mean temperature averaged 9.36°C, a value well above the long-term average of 9.00°C and considerably higher than was seen for cycle 21 (9.03°C; see Figure 1). Consequently, for cycle 23 and Hale cycle 7 (cycles 22 and 23) one expects cyclic averages to be above average, as well. This, especially, will be true if, on the basis of solar-cycle forcing, cycle 23 happens to be a stronger than average size

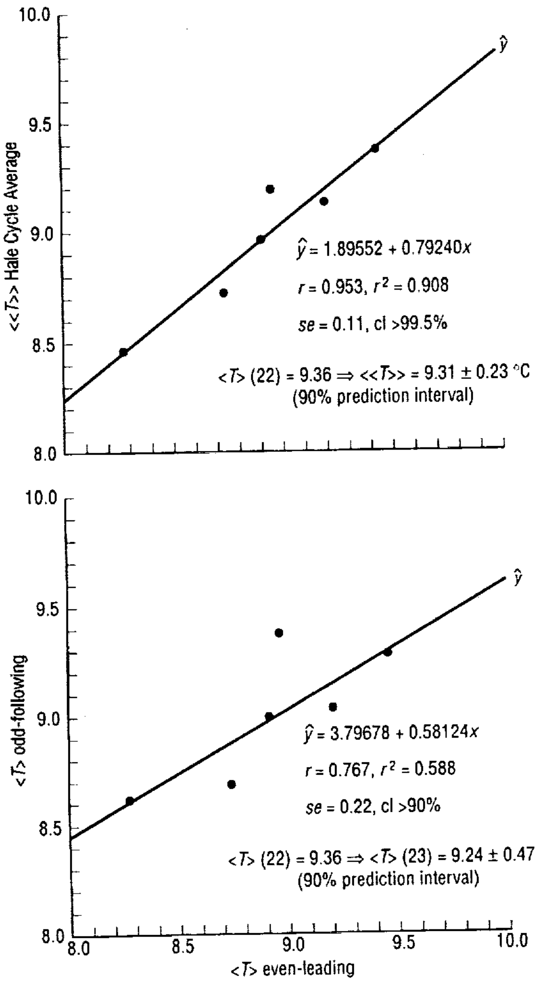

Figure 11. The even-odd cycle effect in *T*. (bottom) <*T*>odd-following cycle average versus <*T*>even leading cycle average. (top) <<*T*>> Hale cycle average versus <*T*>even-leading cycle average.

cycle as, statistically speaking, it should be [e.g. *Joselyn et al.*, 1997; *Kane*, 1997; *Wilson*, 1992; *Wilson et al.*, 1996d, 1998]. Supporting this conclusion is that, if cycle 23 turns out to be stronger than average in size, then its length, probably, will be shorter than average [e.g., *Wilson et al.*, 1996a, c], implying that Hale cycle 7 will be shorter than average, as well and, consequently, that its cyclic average temperature will be warmer than average. For cycle 23, one estimates <*T*> = 9.36 ± 0.36°C (based on the overlap of various predictions presented in the text), and for Hale cycle 7, one estimates <<*T*>> = 9.31 ± 0.23°C. Thus the recent warming trend that began in 1982 appears, likely, to continue into the next millennium.

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