The Use of Cumulative Monthly Mean Temperature Anomalies in the Analysis of Local Interannual Climate Variability

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ABSTRACT

The Edmonton monthly mean temperature record has been examined using the concept of the cumulative high frequency monthly mean temperature anomaly, *I*. The time sequence of *I* is shown to exhibit bounded, oscillatory, nonperiodic behavior.

At times features such as annual and quasi-triennial cycles and sudden reversals are exhibited. Some implications of these observations for interannual climate modeling and forecasting are discussed.

1. Introduction

The use of cumulative variables in the analysis of climate problems is not new. It derives from the idea that certain climate-driven quantities respond not only to the "instantaneous" climate, but to the accumulated effects of climate variables over a period of time. Changnon (1987) and Lawford (personal communication) have used cumulative monthly or annual basin precipitation in their interpretation of lake level fluctuations. In agriculture and the energy industry, the use of growing and heating degree-days for analysis and prediction purposes is also well established. In this paper, we examine cumulative monthly mean temperatures over an extended time sequence—100 years of record at Edmonton, Canada. The analysis reveals a structure to the cumulative temperature data, which has implications both for climate theory and for interannual extended range forecasting.

There is a popular belief, especially prevalent in midlatitudes, that if we have experienced an extended spell of good weather (e.g., warmer than "normal"), we will have to "pay" for it at sometime in the future with a spell of poor weather (e.g., colder than "normal"). Examples of this belief range from the farmer who says, "The longer this drought lasts, the sooner we'll have rain. It all averages out," to prestigious scientific committees that proclaim, "Our instincts about the historical record have assured us that the earth returns, despite the severity of any single event, to a time-honored mean." (NSF 1987). This notion derives from the well-known fact that both weather and climate tend to fluctuate around the "normal." If this were not so, the idea of the "normal" would not be very useful and, indeed, could probably not be defined.

The sources of local short-term fluctuations (several days) in midlatitude weather are the well-known midlatitude cyclones and their associated upper short waves. Longer term fluctuations (several weeks) are connected with the upper long waves, extended spells of anomalous weather being associated frequently with blocking. This paper looks at even longer term fluctuations (several years). For this reason we will consider monthly mean temperatures, which will, to some degree, filter out day-to-day and week-to-week effects. The objective is to gain some quantitative insight into the notion of climatic compensation referred to above, with a view to local climate forecasting on an interannual time scale.

2. Edmonton monthly mean temperatures

Figure 1 illustrates the 101-year time sequence of Edmonton monthly mean temperatures from 1888 to 1988. The observing site was moved several kilometers within the city in 1912 and again in 1937. There were also moves in 1950, 1958, and 1975, each less than 100 m. We have not attempted to correct for any effects of these moves on the temperature data because a comparison with nearby stations (with shorter records), that were not moved or were moved at other times, suggests that there was no influence of the move on the interannual fluctuations. The annual cycle is apparent in Fig. 1. It clearly dominates the signal, although it is possible to identify extreme anomalies, such as the winter of 1935/36. Because of our interest in anomalies (spells of warmer or colder than normal conditions), our first step is to remove the "normal" annual cycle. This is a straightforward procedure once we define what we mean by "normal." Ideally, an en-

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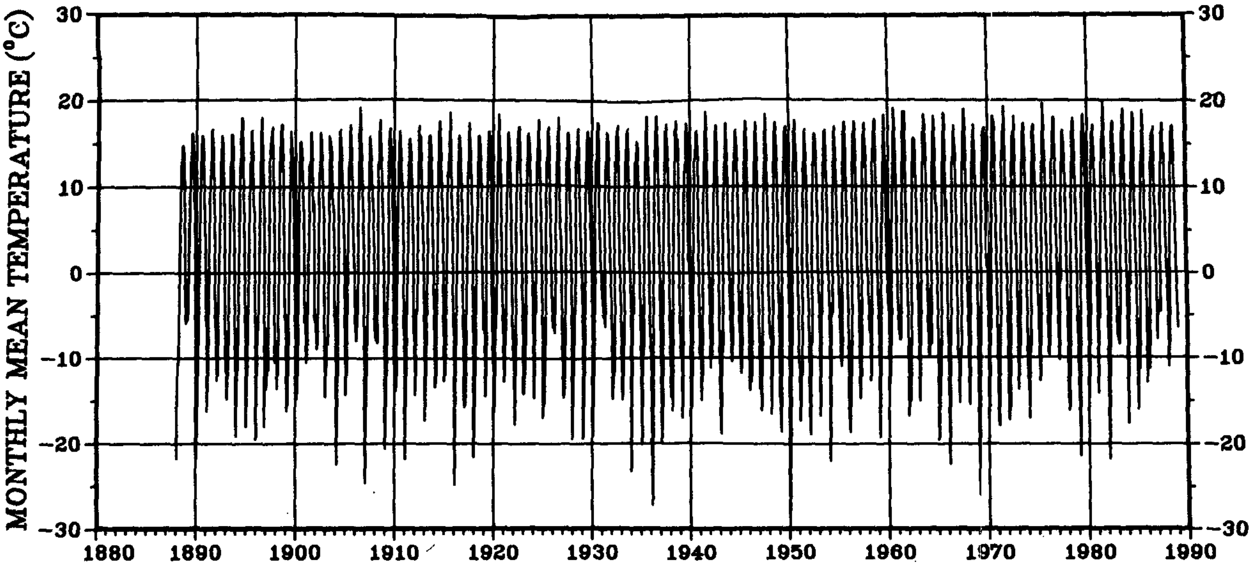


FIG. 1. Monthly mean temperature for Edmonton, 1888–1988.

semble mean over an infinite number of climate "realizations" is what we would like to use (Leith 1984). However, in practice we are forced to use some sort of time average, and for our purpose we have chosen the mean, month-by-month, for the entire sequence. After subtracting the "normal" annual cycle, the monthly mean temperature anomaly sequence appears as in Fig. 2. From this graph it is easier to pick out unusually warm or cold months. It is also possible to see a 101-year trend from a surplus of cold months towards an excess of warm months. Nevertheless, the signal gives the appearance of "random" noise, and apart from the fact that over the period of record the positive and negative anomalies must cancel each other, we seem

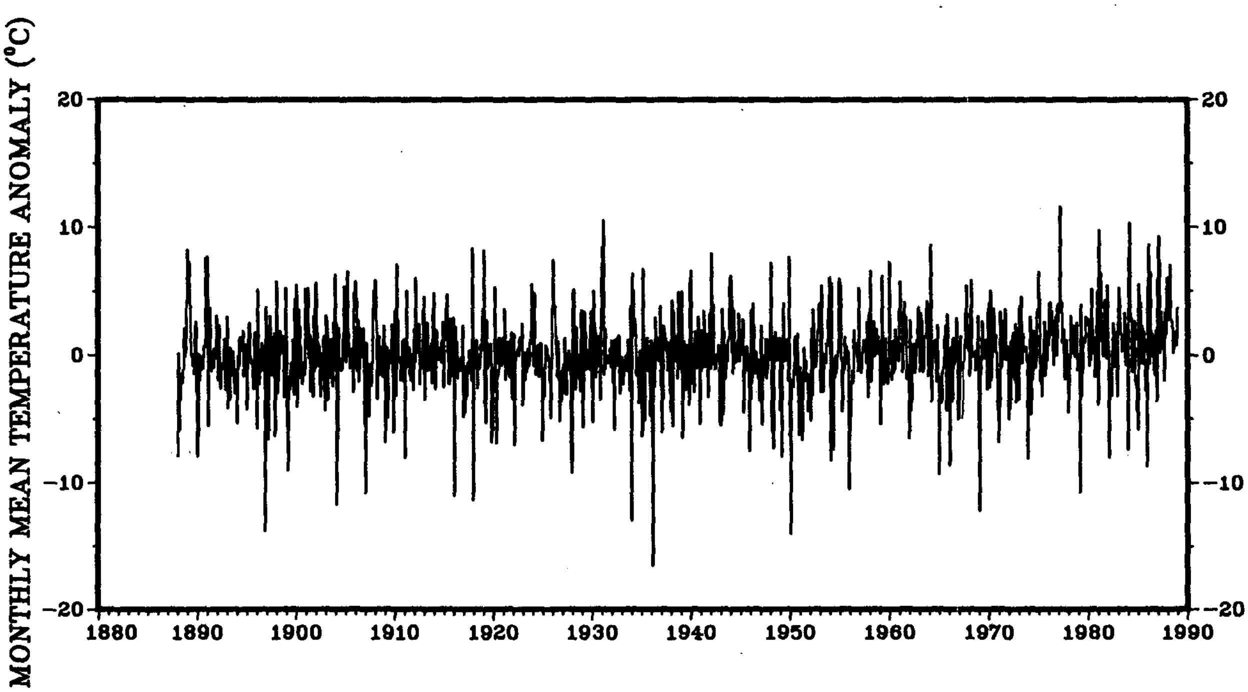


FIG. 2. Monthly mean temperature anomaly for Edmonton.

to be no further ahead in terms of exploring the climatic compensation notion referred to in the Introduction.

It is here that the examination of cumulative temperature anomalies may be helpful. Since "extended spells" of anomalous surface temperatures may be associated with anomalous heat transfer with the ground or ocean, the cumulative temperature anomaly may serve as a measure of the anomalous heat deposited into or withdrawn from these reservoirs. The cumulative temperature anomaly should have the additional advantage of effectively filtering some of the high frequency "noise" without actually losing any of the signal. Thus persistent anomalous spells will appear as trends in the graph of cumulative temperature anomaly. In Fig. 3, we show the result of summing the monthly mean temperature anomalies (ab init., 1888) and plotting the resulting time sequence through to the present.

A few words should be interjected here about the interpretation of Fig. 3. Klemes (1974) has examined some of the properties of cumulative stochastic time series, and the reader is encouraged to consult this paper. The cumulative temperature anomaly, I, is related to the anomaly itself, T, according to

$$I = \sum_i T_i, \qquad (1)$$

where the summation is over months, starting at the beginning of the record. This may be viewed as an approximation to the relation

$$I = \int_0^t T dt \qquad (2)$$

from which we have

$$T = \dot{I}, \qquad (3)$$

where the dot represents differentiation with respect to time. Hence the month-to-month change of the curve in Fig. 3 yields the monthly mean temperature anomalies. Thus none of the data are actually lost through this procedure, even though it is apparent that Fig. 3 is not as "noisy" as Fig. 2.

In view of Eq. (3), we may also write:

$$\dot{T} = \ddot{I}. \qquad (4)$$

Thus temperature anomaly trends are related to the curvature of $I(t)$, upward concavity implying warming and downward concavity cooling. With this in mind, we can see one of the disadvantages of looking at $I(t)$, rather than $T(t)$. While insensitive to random noise and errors, $I(t)$ is quite sensitive to systematic errors and trends. Thus the warming which began in the 1950s dominates the signal. There also appear to be other fluctuations of both long period (a decade or more), and short period (a decade or less).

In this paper, we wanted to focus on fluctuations of

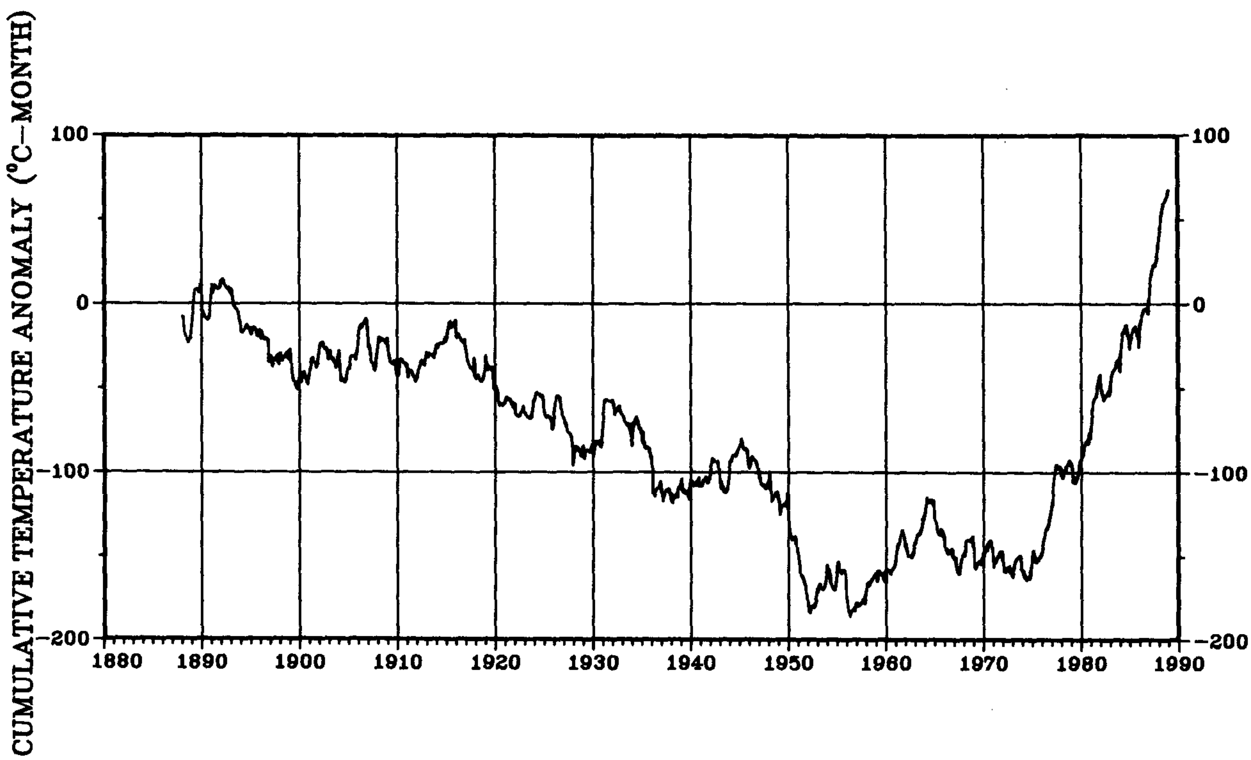


FIG. 3. Cumulative monthly mean temperature anomaly for Edmonton.

intermediate time scale (2 years to 2 decades). In order to do this, we first applied a low pass filter to the raw monthly temperature anomalies. This was a 145 point Gaussian filter with a standard deviation of 21.2 months, the latter choice being made to correspond with the filter used by Jones et al. (1986). This yields a filtered monthly anomaly, T_f, which is plotted as a smooth curve in the background of the raw monthly anomalies in Fig. 4, and with the annual temperature anomalies in Fig. 5. It is apparent from Fig. 5 that T_f faithfully follows the long term (decadal) variations of the annual anomaly signal. Thus it could be thought of as representing the slow variation of the climate "normals." We will not speculate on the cause of the post-1950s warming, beyond suggesting that it is unlikely to be due to the very minor station location changes in 1950, 1958, and 1975. An urban heat island effect due to the growing city size can also be ruled out, as a virtually identical warming is evident in the record of the rural station at Calmar about 50 km to the southwest of Edmonton.

By subtracting the low frequency filtered annual anomaly, T_f, from the monthly mean anomaly, T, we generated a high frequency residual anomaly, T_h. Summing T_h yields the cumulative high frequency temperature anomaly curve (Fig. 6), where the initial value of T_h (at first set arbitrarily to zero) has been chosen to yield a mean T_h of zero over the entire record. Comparing Fig. 6 with Figs. 3 and 4 verifies, visually, that the intermediate frequency signal has been retained, while long and short period variations have been removed. We have thus, in effect, processed the time series through a band-pass filter.

The amplitude response function of this filter is derived in the Appendix and is plotted in Fig. 7. The half-power bandwidth is 2.5 to 16.7 years, while the half-amplitude bandwidth is 3.5 to 20.8 years. Thus, this is a wide band-pass filter that effectively suppresses only the long period variation of the climate "normals" and the high frequency weather noise. This should leave the influence, if any, of such physical processes as the quasi-biennial oscillation, El Niño, and the sunspot cycle, in the resulting time series.

Figures 8a and 8b show the power spectra for the raw anomaly time series and for the cumulative high frequency anomaly time series, respectively. These were produced with the IMSL.STATLIB (International Mathematics and Statistics Library), using a Daniell window with half-width parameter m = 300. Both spectra are truncated at a frequency of 0.1 month^{-1}, although both were calculated up to a frequency of 0.5 month^{-1}. The raw anomaly spectrum (Fig. 8a) gives the impression of white noise. There are noticeable peaks at 0.9 years, 1.4 years, 1.8 years, 2.3 years, 2.6 years, and 3.3 years. However, as these were found to shift about with changes in the width of the Daniell window, they would not appear to have any physical significance. This result is in contrast to that of Georgiades (1977) who examined the power spectrum of annual temperature anomalies at Saskatoon (500 km

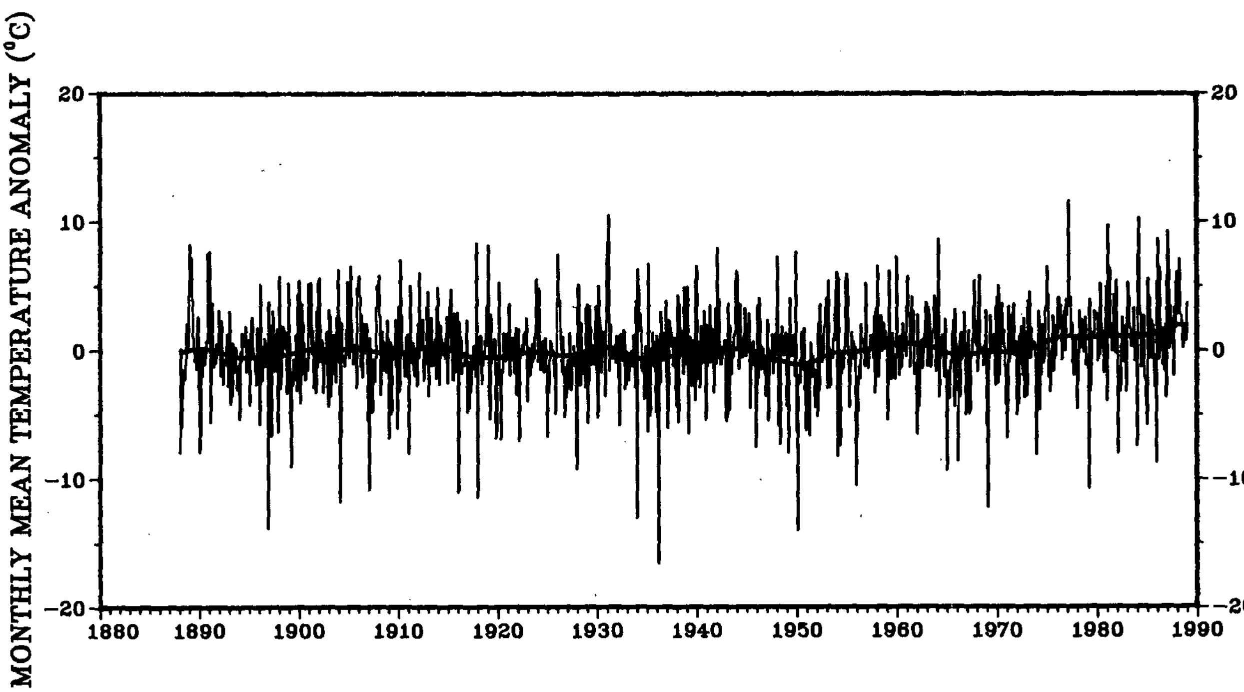


FIG. 4. Monthly mean temperature anomaly with Gaussian filtered monthly temperature anomaly (smooth curve) in the background, for Edmonton.

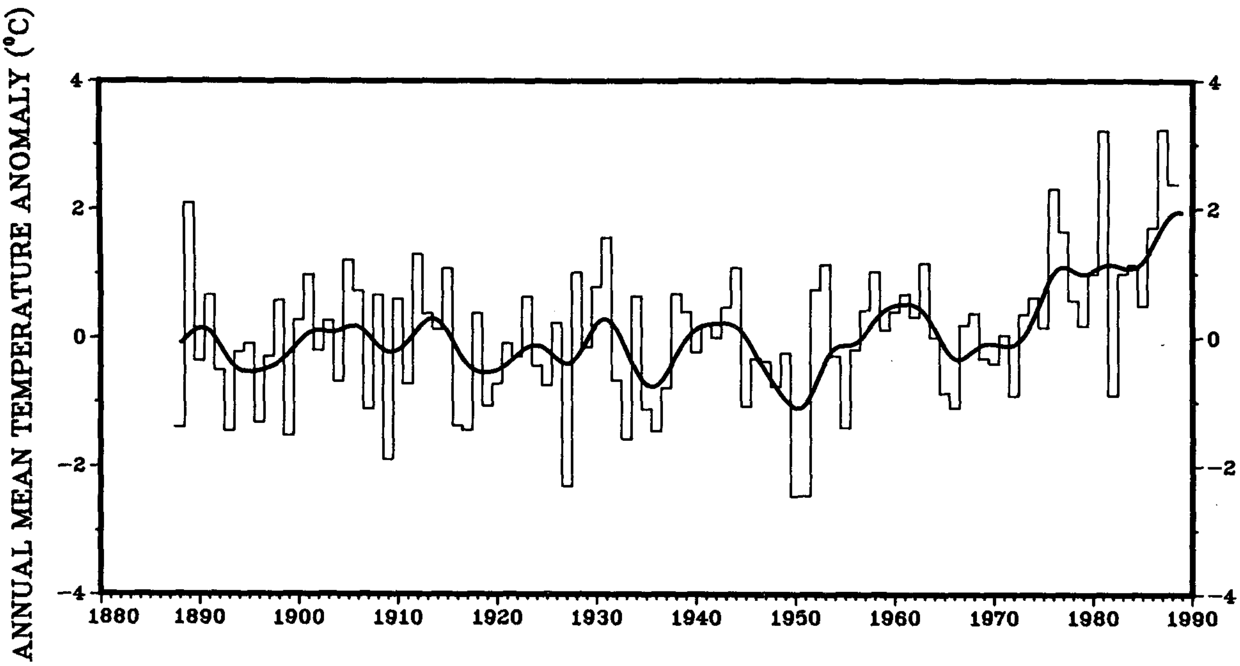


FIG. 5. Annual mean temperature anomaly for Edmonton, along with the Gaussian filtered monthly temperature anomaly (smooth curve).

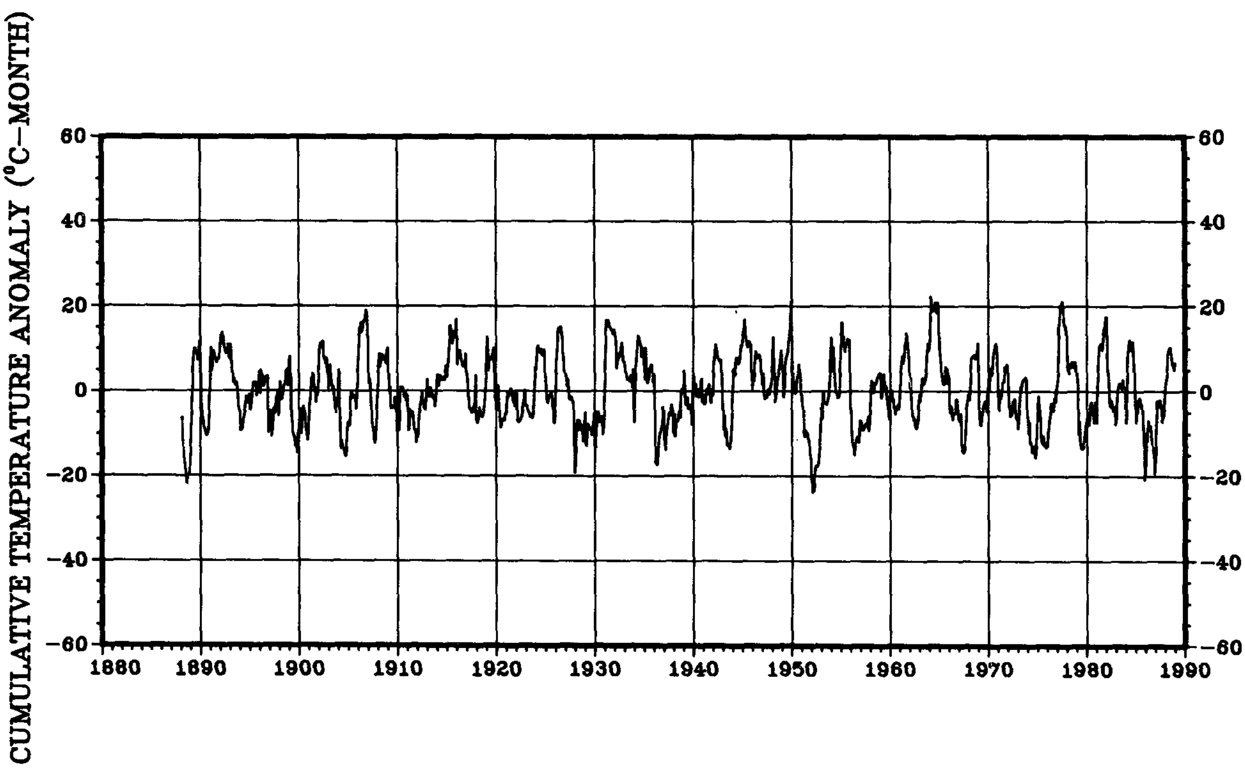


FIG. 6. Cumulative high frequency temperature anomaly for Edmonton.

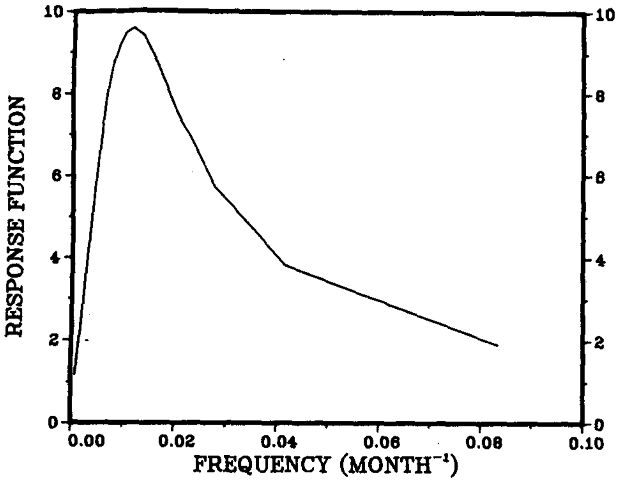


FIG. 7. Amplitude response function of the band pass filter used in this study, as derived in the Appendix.

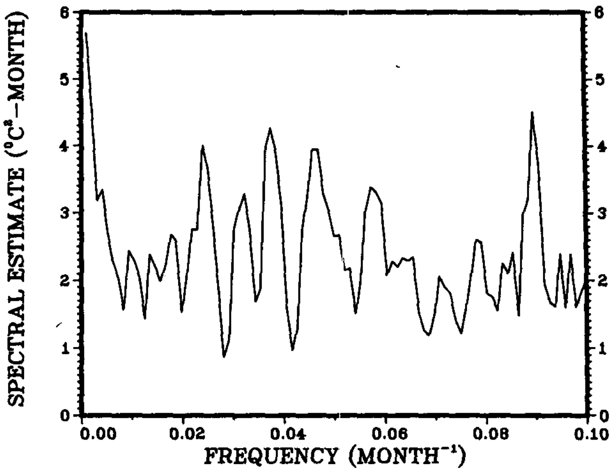


FIG. 8(a). Power spectrum of the raw monthly mean temperature anomaly series shown in Fig. 4.

east of Edmonton). He was able to identify peaks at 2.6 years and 5.0 years, significant at the 99% level. The cumulative high frequency anomaly spectrum (Fig. 8b) exhibits a strong band ranging from about 3.1 years to 18.5 years. This is essentially the half-power bandwidth of our band-pass filter. Within this band, there are four distinct lines at 3.3 years, 4.5 years, 7.6 years, and 13.9 years. We are aware of no physical mechanism to explain any of these lines. Moreover Schönwiese (1987) has shown that this type of analysis can be misleading since the spectrum may vary with time. Consequently, we will confine our inferences about oscillatory or quasi-periodic behavior of the anomalies to what may be inferred from the I curve of Fig. 6.

Two observations may be drawn from a visual inspection of Fig. 6. The first is that there is a tendency for periods with generally below normal temperatures (negative slope) to follow periods with above normal temperatures (positive slope) and vice versa. The second is that there is also a tendency for generally above or below normal temperatures to persist for intervals of several months to several years. Although simple (month-to-month) persistence is not always apparent, one can identify a longer term persistence. Together, these results imply that the short term "memory" of the climate system, associated with the oscillations in I, is of the order of several months to a few years. This may arise from interactions between the atmosphere, clouds, oceans, land and cryosphere (Lozowski et al. 1989).

Two other features of Fig. 6 are also apparent. The first is that the amplitude of the oscillation is limited, with a couple of exceptions, to about ±20°C months. The second is a tendency towards exhibiting an annual or triennial oscillation on occasion (since 1976, for example). This type of oscillatory behavior is reminiscent of the chaotic solutions, which have been devised to represent various aspects of weather and climate on different time scales than those considered here (Lorenz 1963; Ghil and Bhattacharya 1979). Perhaps we may be seeing here a self-sustained internal oscillation of the climate system (Robock 1978) driven by (and therefore a subharmonic of) the annual cycle, and controlled by nonlinear feedbacks such as the cloud-albedo or snow-albedo mechanism (Brier 1978). This is speculation for the moment, but the possibility could be addressed through the development and testing of such a model. While we do not presume to have done this, it is conceivable that an equation of the form (Brier 1978):

$$\ddot{I} + f(I, \dot{I}) + g(t) = 0, \qquad (5)$$

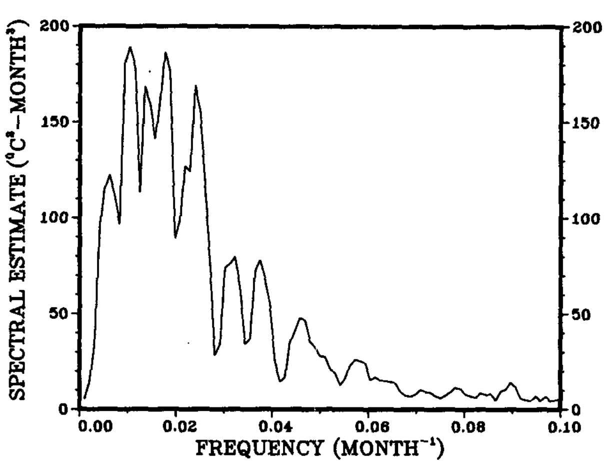


FIG. 8(b). Power spectrum of the cumulative high frequency temperature anomaly series shown in Fig. 6.

could describe the observed oscillation. Here the dot again represents differentiation with respect to time, $g(t)$ is the annual driving term and $f(I, \dot{I})$ is a nonlinear function that may include damping and nonlinear feedback effects. Since the monthly temperature anomaly, T, is one component of a measure of anomalous heat transfer, it would be appropriate to explore heat transfer with the land and oceans in conjunction with the development of such a model. Because $\dot{I} = T$, this equation may also be written as

$$\dot{T} + f(I, T) + g(t) = 0. \quad (6)$$

Thus an understanding of the physics and mathematical solutions of such an equation may provide a basis for short term (several months) prediction of the temperature anomalies, given a knowledge of the current anomaly, T, and of its integrated history, I. This would certainly be an improvement for short term climate forecasting over using persistence or simple extrapolation of the I time sequence (Land and Schneider 1987; Nicholls et al. 1984). There is even some hope that the specific form of Eq. (5) could be "reconstructed" from the time series itself, if it were long enough.

If such a model were developed, certain other features of the time sequence in Fig. 6 would need to be considered. These include the sudden reversals from negative to positive anomalies, and, less frequently, from positive to negative anomalies (as evidenced by the sometimes sharp maxima and minima). An example is the sudden reversal at the beginning and also at the end of 1986. A closer examination of cumulative daily temperature anomalies near the end of 1986 (Fig. 9), shows that this reversal occurred over an interval of a few days, suggesting that the reversal was associated with a rapid change between two persistent long wave patterns. Most of these sudden reversals occur in winter. Those that occur during summer are usually more gradual or less persistent. The explanation for this difference lies in the nature of the temperature anomaly distribution.

The distributions of the high frequency monthly temperature anomalies, T_h, for the entire year—for summer (June to August) and for winter (December to February)—are shown in Fig. 10. The summer anomalies range from +5° to −4°C, while the winter anomalies range from +12° to −17°C. Thus it is not surprising that large anomaly reversals tend to occur in winter, and smaller ones in summer. This suggests that part of the explanation of the annual oscillation in the I curve since 1982 may be "warm" late winters followed by "normal" summers and "cool" early winters. Figure 11 shows details of the I time sequence since 1976. In view of the very regular behavior in recent years and the boundedness of the oscillation,

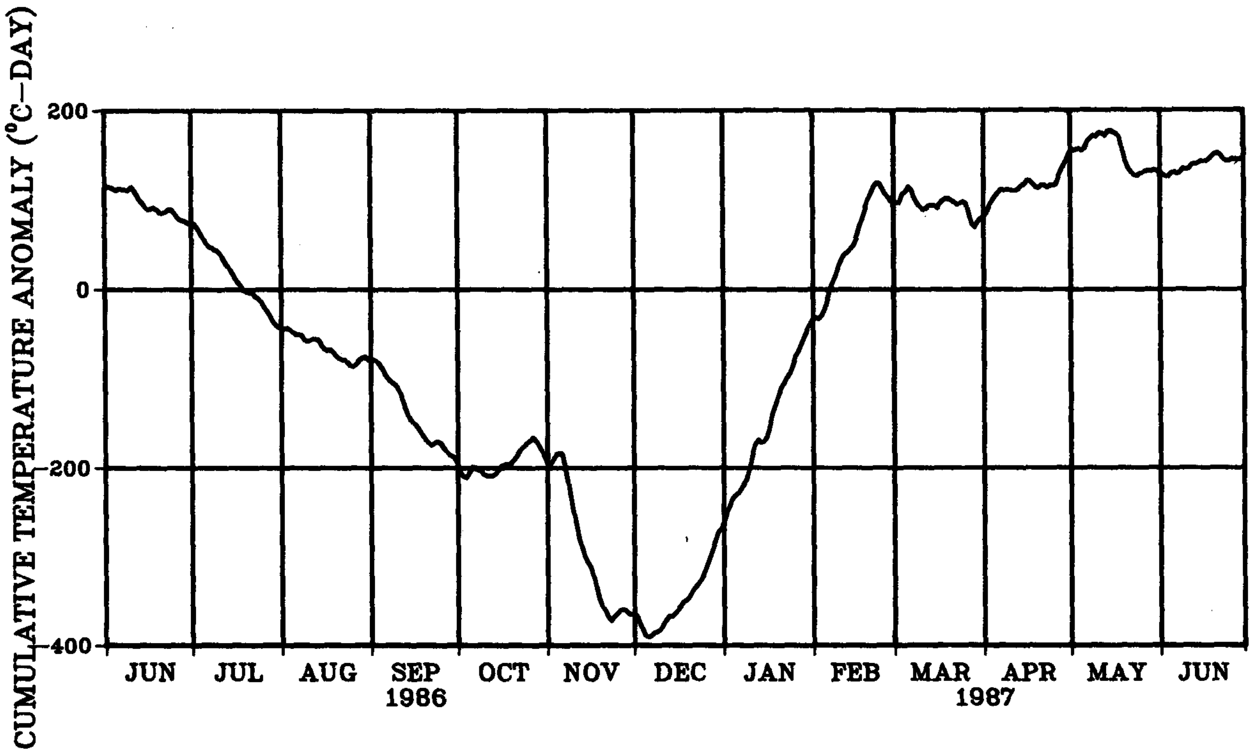
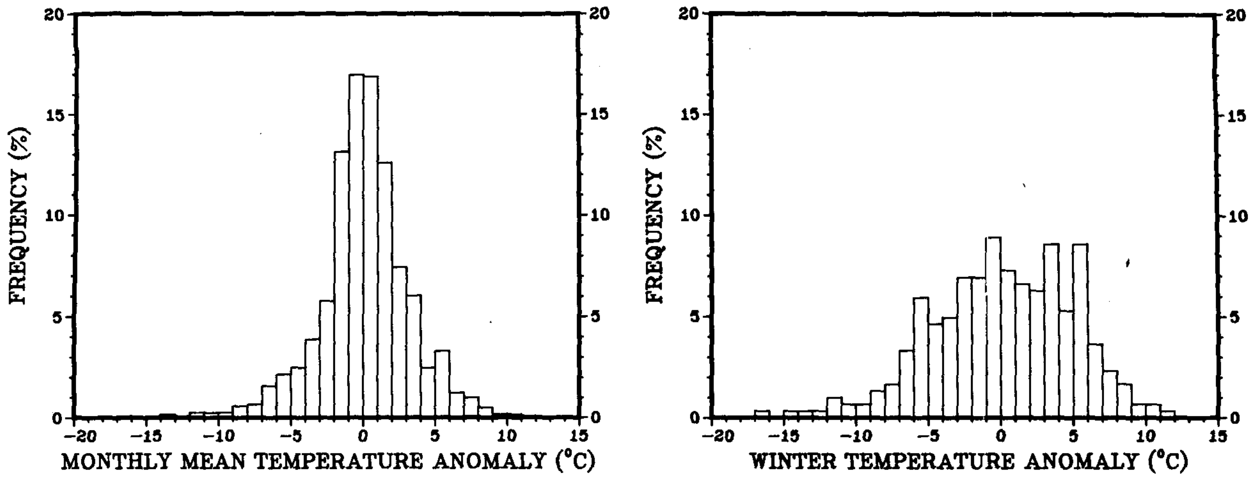


FIG. 9. Cumulative daily mean temperature anomaly near Edmonton from June 1986 to June 1987 (after subtracting a linear trend). Since daily Edmonton data were not available, data from the station at Ellerslie, about 20 km south of the Edmonton station, were used.



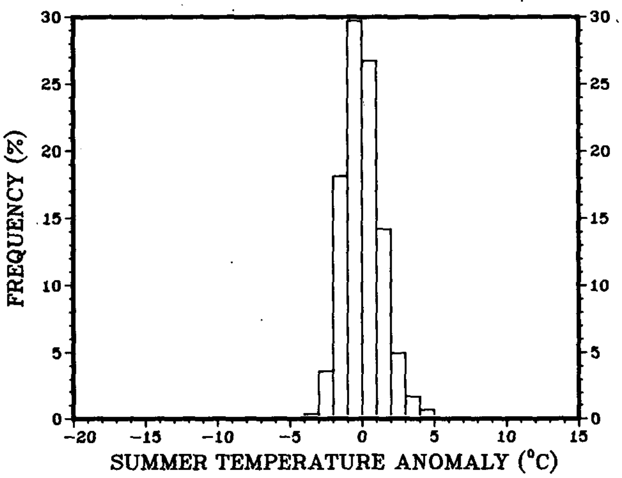


FIG. 10. (a) Distribution of all high frequency monthly mean temperature anomalies for 101 years of data at Edmonton. (b) Same as (a) but for winter (DJF) only. (c) Same as (a) but for summer (JJA) only.

there may be a tendency to think that the time sequence could be extrapolated into the future (at least for a few months to a year or so) with some confidence. While this possibility is an exciting one and deserves further consideration as a possible extended range forecasting tool, we are obliged to express some notes of caution. First, there is evidence that the recent regular behavior is itself an anomaly. We cannot at present forecast how long such regularity is likely to persist. Second, the construction of the *I* curve involves the use of the Gaussian filter, a weighted running mean, which can only be brought up-to-date by generating bogus anomaly values for 6 years into the future. These bogus data can at best be an educated guess (see the Appendix for details) and consequently, the trend of the *I* sequence over the final 6 years of record must be viewed circumspectly. This may explain why the peaks in Fig. 9 have been declining from around 20°C month to about 10°C months over the last 6 years. In view of this, one must resist the temptation to forecast generally negative anomalies for 1989.

3. Summary and conclusions

The use of cumulative monthly mean temperature anomalies is a worthwhile approach to studying interannual climate fluctuations, because they reveal time varying structures in the data that do not readily appear in the raw data or in the more traditional statistical analyses. They may also provide a basis for extended range temperature anomaly forecasting. They must be used with caution, however, because they are susceptible to systematic effects and errors. One must also be very careful if extrapolation is attempted.

Examination of the *I* curve for Edmonton has revealed support for the notion of extended "persistence" over several months to several years, even though simple month-to-month persistence may not be evident. It has also revealed a bounded, nonperiodic, oscillatory behavior that exhibits, from time to time, certain characteristic structural features. These include an annual oscillation, a quasi-triennial oscillation and sudden anomaly reversals. The boundedness of the oscillation

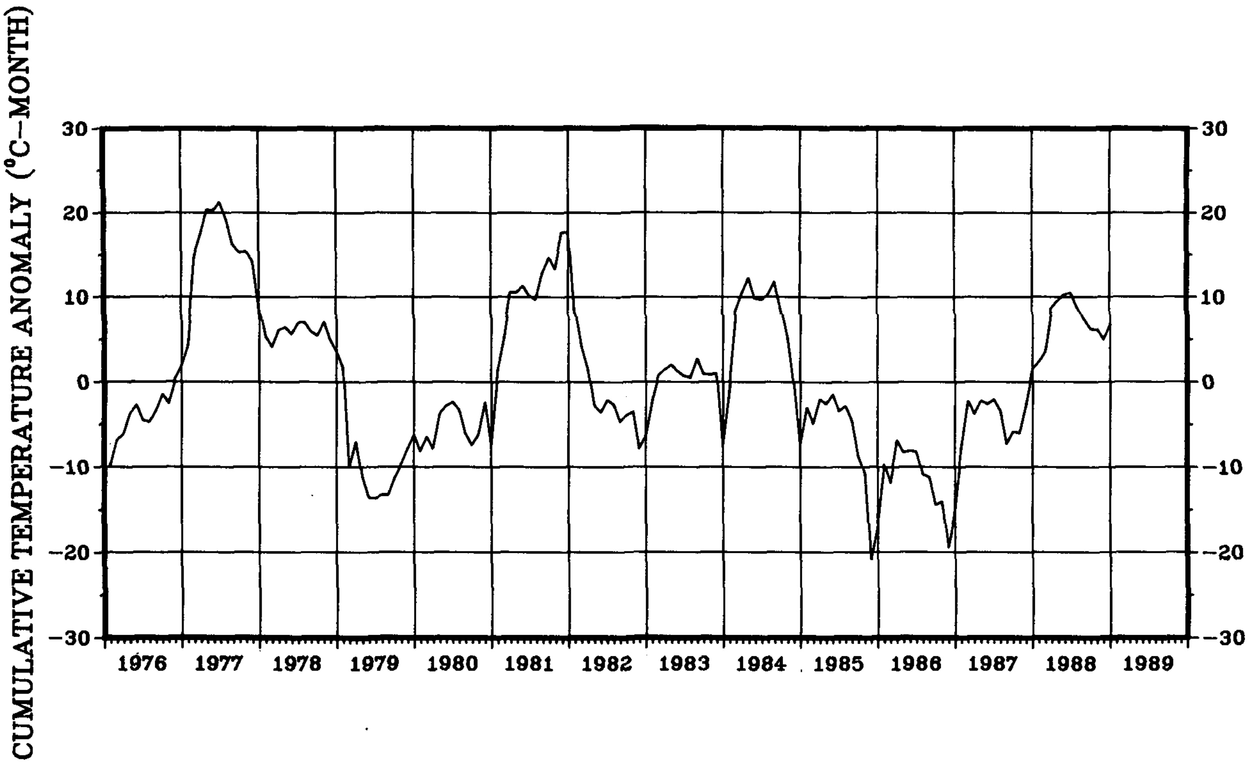


FIG. 11. Same as Fig. 6 but for the years 1976–88.

supports the notion of climate compensation; i.e., that spells of cold anomalies must eventually follow spells of warm anomalies. Any model of local interannual climate variability must take these features into account.

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APPENDIX

Filter Characteristics

The filtering procedure which has been used in this paper consists of two parts. First the annual cycle is removed by subtracting the "climatological" monthly mean temperature from the actual monthly mean temperature. For each month, the "climatological" value is estimated by averaging the monthly mean temperatures for that month over the entire series. We believed that using the entire series would yield a more stable estimate than using the 1951–80 period, which is the period currently in use for defining climatological "normals." We call the resulting series the monthly mean temperature anomalies (MMTA).

It is to the latter series that we apply the band-pass filtering procedure described in the text. In what follows, we will derive the amplitude gain function (frequency response function) for this procedure. Let m_j be the series of MMTAs. From this we generate a low-pass filtered MMTA series, fm_j, as follows:

$$fm_j = \sum_{k=-72}^{72} w_k m_{j+k} \qquad \text{(A1)}$$

where the Gaussian weights are given by

$$w_k = \frac{1}{\sigma\sqrt{2\pi}} e^{-k^2/2\sigma^2}, \qquad \text{(A2)}$$

with $\sigma = 21.22$ (k and σ carry implicit dimensions of months), a value chosen so that the resulting filter yields a filtered series similar to that of Jones et al. (1986). The 72 month half-width of the filter was chosen so that, to a good approximation,

$$\sum_{k=-72}^{72} w_k \doteqdot 1. \qquad \text{(A3)}$$

In order to apply this filter from the very first to the very last month of the MMTA series, we had to generate 72 months of bogus data at the beginning and 72 months at the end of the series. Data for each month of the bogus series was generated as follows. Let us consider the initial bogus series first. Each month of the bogus years was assigned a monthly mean temperature anomaly equal to the average temperature anomaly for that month during the first 6 years of the observed series. Data for the terminal bogus series were generated analogously by using the final 6 years of the observed series. The series fm_j appears as the smooth curve in Fig. 5.

We obtain the high-pass filtered MMTA by subtraction:

$$ma_j = m_j - fm_j. \qquad (A4)$$

Denoting Fourier transforms by upper case symbols, we thus may write

$$MA(f) = M(f) - FM(f), \qquad (A5)$$

where f denotes frequency and

$$FM(f) = W(f)M(f), \qquad (A6)$$

with $W(f)$ the Fourier transform of the weighting function w_k.

We complete the band-pass filtering procedure by accumulating ma_j; i.e., we define a cumulative monthly mean temperature anomaly series, cma_j, as follows:

$$cma_j = \sum_{k=1}^{j} ma_k. \qquad (A7)$$

The series cma_j is shown in Fig. 6.

Since this is a finite approximation to an integration in time, we may write, in the frequency domain

$$CMA(f) = \frac{MA(f)}{j2\pi f}. \qquad (A8)$$

Hence using Eqs. (A5) and (A6):

$$\frac{CMA(f)}{M(f)} = \frac{1 - W(f)}{j2\pi f}. \qquad (A9)$$

The left-hand side of Eq. (A9) is the desired amplitude gain. This has been plotted, in Fig. 7, by evaluating $W(f)$ as:

$$W(f) = W_0 + 2\sum_{k=1}^{72} w_k \cos 2\pi fk, \qquad (A10)$$

which corresponds to the moving weighted average operation used in the low-pass filtering.

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