A Study of Climatic Variability

G. J. BOER AND K. HIGUCHI

Canadian Climate Centre, Downsview, Ontario, Canada M3H 5T4

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ABSTRACT

An analysis of variance of the 1000–500 mb thickness field is performed to investigate climatic variability from 1949 to 1975. The thickness field and its variance, averaged over the Northern Hemispheric cap from 25°N latitude to the pole, are obtained and the resulting time series are analyzed for their trends and interrelationships.

Analysis of the mean thickness and measures of transient eddy, standing eddy and north-south variance shows a statistically significant linear trend in mean thickness and significant quadratic trend in standing eddy and north-south variance measures. No significant trend is found in transient eddy variance.

Correlation analysis of the time series shows a significant relationship between standing and transient eddy variances. No significant correlation between the mean thickness and the eddy terms nor between the north-south variance and the eddy terms is found.

The results of this study do not support the contention that the climate has become significantly more variable, nor do they support a connection between variability and either mean temperature or north-south variation of temperature.

1. Introduction

In recent years there has been increasing concern about climatic change and variability and its influence on man and his activities. This concern has been formally expressed in a WMO statement on climate change and variability (WMO, 1976).

Many studies concerning climatic change have been undertaken. Most studies have concentrated on long-term trends in temperature. Recent studies of this kind include those of Starr and Oort (1973), Angell and Korshover (1975, 1977) and Damon and Kunen (1976). Other quantities have received some attention, notably snow and ice cover (Kukla and Kukla, 1974). A survey article by Kukla *et al.* (1977) presents a large variety of observed climatic parameters. The article deals with zonal- and time-averaged quantities and is directed toward identifying trends.

While the importance of identifying and understanding historical trends in the climatic record is clear, some measure of "variability" also demands examination. There appears to be a general belief that the climate has become more "variable" in recent times. For instance, there is the suggestion that "since the 1940's and 1950's . . . the atmospheric circulation in the Northern Hemisphere appears to have shifted in a manner suggestive of an increasing amplitude of the planetary waves and of greater extremes of weather conditions in many areas of the world" (GARP, 1975, p. 16).

Two recent papers that have addressed themselves to some aspects of this question are those of Angell and Korshover (1978) and van Loon and Williams (1978).

The purpose of the work reported here is to investigate climatic variability in the past 25 years in as simple and straightforward a way as possible via an analysis of variance of the 1000–500 mb thickness field.

2. Data

Twice daily latitude-longitude grid point values of the 1000–500 mb thickness for the Northern Hemisphere region poleward of 25°N latitude are used in this study. The data were obtained from the British Meteorological Office (Moffitt and Ratcliffe, 1972). They cover the period 1949–75.

Data over the Pacific Ocean south of 55°N latitude are missing prior to 1965. For that period therefore the area-averaged statistics contained no contribution from this Pacific area. The importance of the Pacifice "gap" was tested by calculating the statistics after 1965 with and without data in this Pacific region. Differences in the results were small.

One difficulty with climatic analysis on analyzed data is the possibility that the analysis scheme used over the period will have changed. In this case there were essentially two sources of data as discussed in Moffitt and Ratcliffe, both based on subjective

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analysis. The change from one analysis scheme to the other occurred at the end of 1965. The study reported here presumes that this change in analysis scheme does not contaminate the climatic record. The results obtained do not appear to be explainable as a result of a change in analysis methods.

3. Definitions

The 1000–500 mb thickness field Δz is a measure of the temperature in the lower half of the atmosphere. It is available in grid-point form which makes it relatively easy to do the kind of analysis of variance that is usual in studies of the general circulation.

It is important to be clear as to the definitions of climatic variability used here. The following averages and deviations therefrom are defined for the dependent variable $X(\lambda,\varphi,t)$, a function of latitude, longitude, and time:

$$\bar{X} = \frac{1}{T}\int_{\tau-T/2}^{\tau+T/2} X dt, \quad X' = X - \bar{X}, \tag{1}$$

$$[\bar{X}] = \frac{1}{2\pi}\int_0^{2\pi} \bar{X} d\lambda, \quad \bar{X}^* = \bar{X} - [\bar{X}], \tag{2}$$

$$\langle[\bar{X}]\rangle = \frac{\int_{\varphi_1}^{\pi/2} [\bar{X}] \cos\varphi d\varphi}{\int_{\varphi_1}^{\pi/2} \cos\varphi d\varphi},$$

$$[\bar{X}]\dagger = [\bar{X}] - \langle[\bar{X}]\rangle. \tag{3}$$

The time averaging is for a month so that the averaged statistics form a time series of monthly values (τ indicates the month number). The integration in space is around latitude circles and over the partial hemispheric cap from latitude φ_1 to the pole. The statistics which arise under these definitions are shown in Table 1. The lowest entries in the table are of primary interest here.

The variability of X as measured by the mean-square deviation of X from its time and space average $\langle[\bar{X}]\rangle$ is

$$\mathrm{var}(X)_\tau = \frac{1}{(1-\sin\varphi_1)}\frac{1}{2\pi}\frac{1}{T} \times \int_{\varphi_1}^{\pi/2}\int_0^{2\pi}\int_{\tau-T/2}^{\tau+T/2} (X - \langle[\bar{X}]\rangle)^2 \cos\varphi d\varphi d\lambda dt$$

$$= \langle[\overline{(X - \langle[\bar{X}]\rangle)^2}]\rangle$$

$$= \langle[\bar{X}]\dagger^2\rangle + \langle[\bar{X}^{*2}]\rangle + \langle[\overline{X'^2}]\rangle. \tag{4}$$

This is a decomposition of the variance of X into three components called here, respectively, the north-south variance, the standing eddy variance and the transient eddy variance.

4. Interpretation

This decomposition of variance is standard in general circulation studies (e.g., Lorenz, 1967; Newell *et al.*, 1972, 1974). The field X is resolved, in this case, into the components

$$X = \langle[\bar{X}]\rangle + [\bar{X}]\dagger + \bar{X}^* + X'$$

using the definitions Eqs. (1)–(3). These components in order are:

1) The time- and space-averaged field.

2) The deviation of the time- and zonal-averaged values from $\langle[\bar{X}]\rangle$. This term would be zero if $[\bar{X}]$ had no north-south variation. It is a measure of the deviation from a "flat" field in the north-south direction, and hence indirectly of the north-south gradient of $[\bar{X}]$.

3) The deviation of the time-averaged field from its zonal average. This term is a measure of the non-zonality of the monthly time-averaged maps. The deviation from zonal symmetry on time-averaged maps is termed the standing eddy component and is a measure of the large-scale standing wave amplitude.

4) The deviation from the time-averaged field. This is a measure of the lack of steadiness in time of the field and is called the transient eddy term. It measures the temporal variability at a point due to migrating eddies and other time fluctuations.

TABLE 1. Statistics under averaging.

	Averaging	Independent variables	Statistics			
Daily data	None	λ, φ, t	X	X'		
Monthly mean statistics	Time average	λ, φ, τ	$\bar{X}$	$\overline{X'^2}$	$\bar{X}^*$	
	Zonal average	φ, τ	$[\bar{X}]$	$[\overline{X'^2}]$	$[\bar{X}^{*2}]$	$[\bar{X}]\dagger$
	North-south average	τ	$\langle[\bar{X}]\rangle$	$\langle[\overline{X'^2}]\rangle$	$\langle[\bar{X}^{*2}]\rangle$	$\langle[\bar{X}]\dagger^2\rangle$
			mean values	temporal deviation and variances	east-west deviations and variances	north-south deviation & variation

The integration over the hemispheric cap in Eq. (4) reduces the dimensionality of the problem. The resulting variance measures are monthly time series. It is impossible, therefore, to consider questions of change in local variability by this kind of analysis; rather the question is whether there has been a change in the total variance or in its components within the region under study.

This approach also allows a straightforward interpretation of the variance components in terms of available potential energies. Using the notation of Eq. (4), the zonal and eddy available potential energies are obtained in terms of integrals of the variance terms over the mass of the region. The Lorenz (1967) approximate formulas are

$$A_z = \frac{1}{2}\int C_p\gamma[\bar{T}]\dagger^2 dm$$

$$= \pi a^2(1 - \sin\varphi_1)g^{-1}\int C_p\gamma\langle[\bar{T}]\dagger^2\rangle dp,$$

$$A_E = \frac{1}{2}\int C_p\gamma([\bar{T}^{*2}] + [\overline{T'^2}])dm$$

$$= \pi a^2(1 - \sin\varphi_1)g^{-1}\int C_p\gamma\langle[\bar{T}^{*2}] + [\overline{T'^2}]\rangle dp,$$

where γ is a stability parameter. A_z and A_E are the zonal and eddy available potential energies respectively.

The 1000–500 mb thickness is proportional to the mean temperature of the layer; that is

$$\Delta z = -Rg^{-1}\int_{500}^{1000} Td\ln p \propto T_{\text{mean}},$$

so that, provided γ does not vary greatly, the variance term $\langle[\overline{\Delta z}]\dagger^2\rangle$ is proportional to the zonal available potential energy (for the 1000–500 mb layer) and the standing and transient eddy variances, $\langle[\overline{\Delta z}^{*2}]\rangle$, $\langle[\overline{\Delta z'^2}]\rangle$ are proportional to the eddy available potential energy.

5. Time scales

As discussed above, daily grid point data are used to obtain the monthly averaged mean and variance terms. The resulting time series of $\langle[\overline{\Delta z}]\rangle$, $\langle[\overline{\Delta z'^2}]\rangle$, $\langle[\overline{\Delta z}^{*2}]\rangle$ and $\langle[\overline{\Delta z}]\dagger^2\rangle$ each have one value for every month from 1949 to 1975. These time series display a pronounced annual cycle. In order to remove this variation from the time series and to concentrate on long time scales, each of the time series is subjected to a 12-month running mean filter. This rather unsophisticated filter does a reasonable job of removing the annual and higher frequency cycles from the time series. What remains, therefore, is the long-period variation. One may then investigate the long-term behavior of the variance measures together with that of the mean using these filtered series.

The filtered time series for the mean thickness and the three variance measures are shown in Fig. 1. The total eddy variance term is shown in Fig. 2. A quadratic trend line is also shown for each of the time series.

6. Relationships between variables

There are several ideas concerning the relationship between these parameters that should be considered. They are: 1) that increased variability is to be expected when the north-south temperature gradient increases—nominally because of the resulting increase in baroclinicity; 2) that periods during which the temperature is relatively low are also periods of increased variability; and 3) that the transient and standing eddy variances will have an out-of-phase relationship. This is based on the concept that predominantly zonal flow is associated with rapidly moving systems and higher values of $\langle[\overline{\Delta z'^2}]\rangle$, while more meridional flow and less rapidly moving systems are associated with relative high values of $\langle[\overline{\Delta z}^{*2}]\rangle$.

The first two points were addressed in quite a different context by van Loon and Williams (1978). They considered the relationship between the interannual variability and the 3-month winter (December, January, February) average temperature and precipitation values at a number of points over North America. Their study is the analog, at a station, of a comparison of the N-year running variance of the series given in Fig. 1a with the long-term trend. They found no evidence of a connection between this measure of variability and either the temperature gradient or generally low temperatures. It should be noted that this interannual variance of the mean bears little resemblance to the three variance measures used here.

Angell and Korshover (1978) also consider some measures of spatial and temporal variability. Unfortunately, their variance measures differ both from those of van Loon and Williams and from those used here. A description of their variance measures will not be given here except to note that they represent interseasonal and interannual variation of the mean temperature. Angell and Korshover conclude that "the available evidence suggests that, on the average, both the spatial and temporal variability of temperature have become greater in recent years."

a. Trends and relationships between trends

Linear and quadratic trends are sought in the four series and tested for statistical significance.

The usual tests for significance of polynomial trends (e.g., Bennett and Franklin, 1961) are not

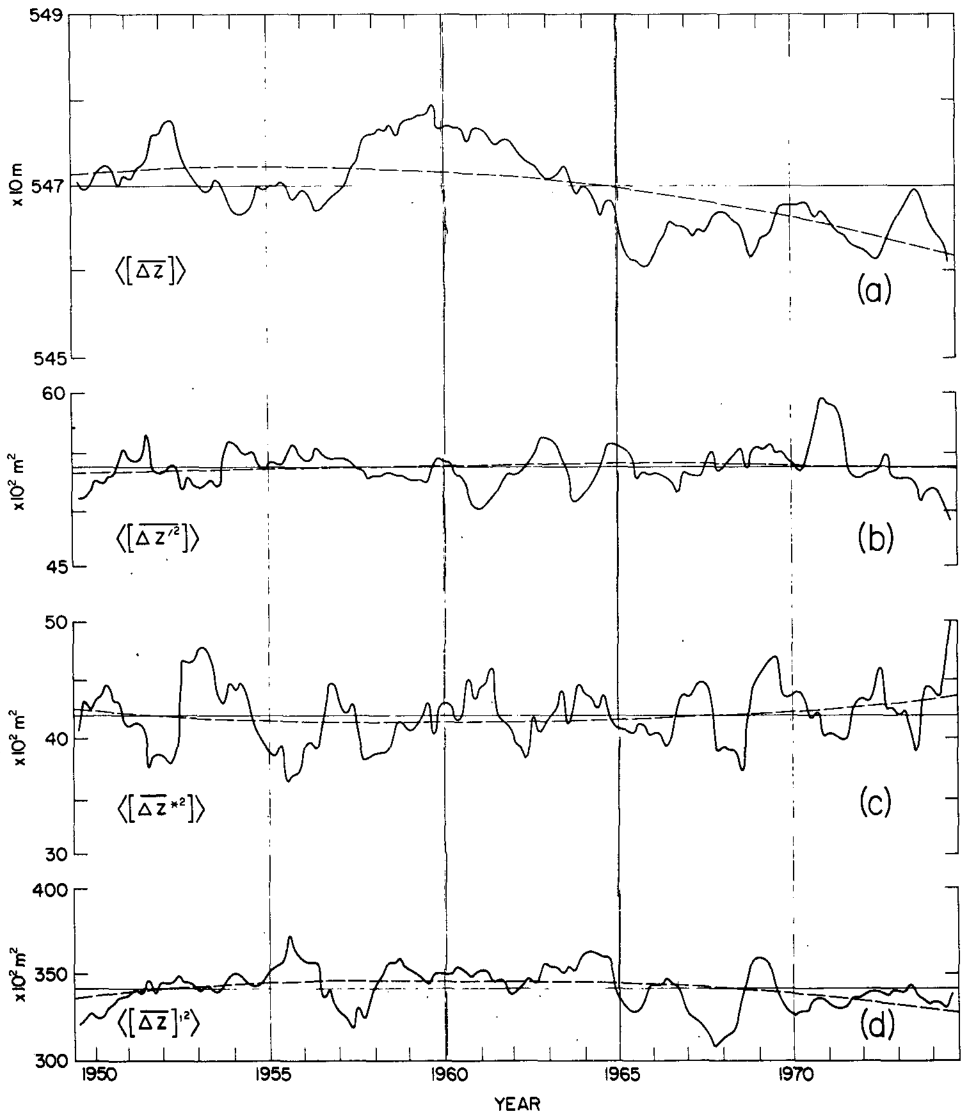

FIG. 1. Smoothed (12-month running mean filter) time series of (a) mean thickness $\langle[\overline{\Delta z}]\rangle$, (b) transient eddy variance $\langle[\overline{\Delta z'^2}]\rangle$, (c) standing eddy variance $\langle[\overline{\Delta z}^{*2}]\rangle$ and (d) north-south variance $\langle[\overline{\Delta z}]^{\dagger 2}\rangle$. In each of the series the dashed line represents a least-squares quadratic fit and the solid horizontal line represents the arithmetic mean of the series.

appropriate as they assume that deviations from the trend line are independent random variables which is not the case for the series considered here. The method used here for assessing the significance of the trends is discussed in Appendix A.

The analysis consists of expressing the series in terms of the orthogonal polynomials $p_1(t)$ and $p_2(t)$ where

$$y = A_0 + A_1p_1(t) + A_2p_2(t), \quad -T < t < T.$$

The polynomials p_1 and p_2 involve linear and quadratic terms, respectively, and the coefficients A_1 and A_2 are tested to see if they are significantly different from zero. The results of this analysis are shown in Table 2. A_i's significantly different from zero are underlined.

The mean thickness (temperature) of the cap as measured by $\langle[\overline{\Delta z}]\rangle$ exhibits a significant linear decreasing trend during the period. This decrease is most marked beginning in the 1960's. This behavior in the mean thickness (temperature) has been noted by a number of investigators as reported in Kukla *et al.* (1977) for instance.

Of the three variance measures (Figs. 1b–1d), the transient eddy variance $\langle[\overline{\Delta z'^2}]\rangle$ (Fig. 1b) exhibits no significant linear or quadratic trends. The stand-

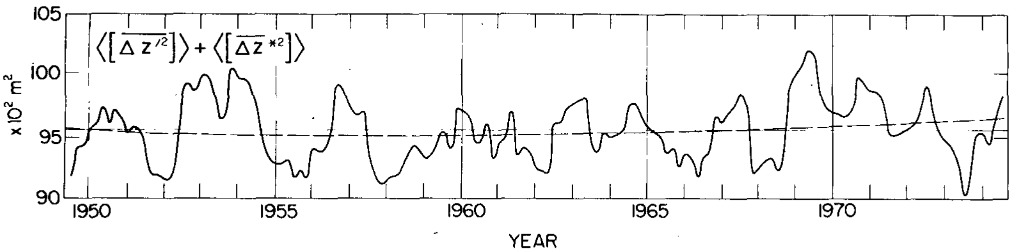

FIG. 2. As in Fig. 1 except for the total eddy variance $\langle[\overline{\Delta z'^2}]\rangle + \langle[\overline{\Delta z^{*2}}]\rangle$.

ing eddy variance $\langle[\overline{\Delta z}^{*2}]\rangle$ (Fig. 1c) and the north-south variance $\langle[\overline{\Delta z}]^{\dagger 2}\rangle$ (Fig. 1d) exhibit significant quadratic trend components but nonsignificant linear trend components. These quadratic trends are of opposite signs with the standing eddy variance term exhibiting a minimum and the north-south variance term a maximum during the period.

The transient eddy variance shows no significant trend and by inspection shows a relatively consistent range of variation with time over the period. One of the more notable local maxima occurred in the early 1970's but this has subsequently decreased. There is certainly no evidence that the temporal variance in the region has changed markedly over the period of record. In particular this term has not changed in response to or in conjunction with the change in mean thickness during the period.

The standing eddy variance displays a significant local minimum during the period. The range of oscillation of this term appears by inspection to be quite uniform. Based on the significant quadratic trend component the long-term behavior of this variance measure can be characterized as having decreased toward the middle of the period and subsequently recovered to previous values. Apparently, this term has not changed in response to or in conjunction with the trend in temperature at least in a direct way since the temperature exhibits only a linear decreasing trend during the period.

Similar remarks apply to the trend in north-south variance. Since the north-south variance is related to A_z, and the standing and transient eddy variance terms to A_E, it is interesting to note that the transient eddy variance does not change in conjunction with the north-south variance while the standing eddy variance changes in the opposite sense as measured by the quadratic trend terms. None of the variance measures exhibits a linear trend as does the mean thickness.

TABLE 2. Estimates of linear and quadratic trends for $y = A_0 + A_1 p_1(t) + A_2 p_2(t)$. Underlined values are significantly different from zero as explained in Appendix A.

Variable	A_1 $\times 10^{-3}$	2 std dev. 10^{-3}	A_2 10^{-5}	2 std dev. 10^{-5}	Units
$\langle[\overline{\Delta z}]\rangle$	$\underline{-3.08}$	1.52	−1.89	2.83	10 m
$\langle[\overline{\Delta z'^2}]\rangle$	−0.96	4.50	−1.85	8.01	10^2 m^2
$\langle[\overline{\Delta z}^{*2}]\rangle$	2.54	3.37	$\underline{7.00}$	5.66	10^2 m^2
$\langle[\overline{\Delta z}]^{\dagger 2}\rangle$	−23.6	26.8	$\underline{-62.1}$	49.4	10^2 m^2

b. Relationships between series

A physical relationship between terms should be expected to apply not simply to the long-term quadratic trends but to the oscillations in the series. In this section an attempt is made to evaluate the evidence for statistical relationships between the series.

The quadratic trends are removed from each of the time series in Fig. 1 and the resulting time series are cross correlated. As discussed above, the adjacent points in the time series are not independent and the usual statistical significance test for the cross correlation is inapplicable. An assessment of the significance of the cross correlation may be made as discussed in the Appendix B, based on techniques given in Bendat and Piersol (1971).

The results of the cross-correlation analysis are shown in Table 3. The only significant relationships between the series is the negative correlation between the transient and standing eddy variances and the positive correlation between the components and their sums. This substantiates this well-known feature of atmospheric behavior on the time scales considered here. Standing and transient eddy heat fluxes for instance are also inversely correlated in this way (van Loon, 1979).

The correlation of the mean thickness value with the other parameters yields no significant values although the magnitudes are reasonably large. The north-south variance measure is apparently quite unconnected with any of the other parameters.

7. Concluding remarks

This study is based on 25 years of daily temperature data (as measured by the 1000–500 mb thickness) over that part of the Northern Hemisphere poleward of 25°N. The behavior in time of the mean temperature together with the monthly mean vari-

TABLE 3. Correlation between variables. Underlined values are significantly different from zero as explained in Appendix B.

	$\langle[\overline{\Delta z}]\rangle$	$\langle[\overline{\Delta z'^2}]\rangle$	$\langle[\overline{\Delta z^{*2}}]\rangle$	$\langle[\overline{\Delta z'^2}]\rangle + \langle[\overline{\Delta z^{*2}}]\rangle$	$\langle[\overline{\Delta z}]^{\dagger 2}\rangle$
$\langle[\overline{\Delta z}]\rangle$					
$\langle[\overline{\Delta z'^2}]\rangle$	−0.25				
$\langle[\overline{\Delta z^{*2}}]\rangle$	−0.13	$\underline{-0.31}$			
$\langle[\overline{\Delta z'^2}]\rangle + \langle[\overline{\Delta z^{*2}}]\rangle$	−0.30	$\underline{0.39}$	$\underline{0.75}$		
$\langle[\overline{\Delta z}]^{\dagger 2}\rangle$	0.14	−0.01	0.00	0.00	

ance of temperature over the region is investigated. The total variance of temperature is decomposed into three components associated respectively with the variation of zonally averaged temperature in the north-south, and the standing and transient eddy variances. These components, in turn, are related to the zonal available potential energy and the eddy available potential energy.

The climatic variables are filtered with a 12-month running mean filter. The resulting series contain only periods longer than a year with appreciable amplitude. The long-term trend lines fitted to these series indicate that the mean temperature exhibits a linear decrease over the period of study, the transient eddy variance exhibits no significant trend, and the standing eddy and north-south variance measures exhibit quadratic trends in opposite senses during the period.

Correlation analysis of the series shows only the well-known relationship between standing and transient eddy variances. No other significant correlations are obtained. In particular, no significant correlation between the mean temperature and the eddy terms nor between the north-south variance and the eddy terms is found.

These results do not support the idea that the climate has become significantly more variable during the period (as measured by these statistics) nor do they support a significant connection between variability and either mean temperature or north-south variation of temperature.

Acknowledgment. We would like to thank John Henderson for computational assistance.

APPENDIX A

The Significance of Polynomial Trends

The statistical model is like that discussed in Bennett and Franklin (1961), namely, that each observation y_α is an observation on a random variable Y which is normally distributed with constant variance and mean $A_0 + A_1p_1(t) + A_2p_2(t)$. Here t is a known parameter and the p_1, p_2 are known functions of t. In this case the p_1, p_2 are the first two orthogonal Gram polynomials of linear and quadratic order respectively. The purpose of the analysis is to decide if the A_1 and A_2 are nonzero.

The observations are assumed to have the form

$$y_\alpha = A_0 + A_1p_1(t) + A_2p_2(t) + z_\alpha,$$

where the A_i are population parameters and the z_α is a stationary random variable with mean zero. In this case the z_α are not taken to be independent so that the autocorrelation

$$R(\alpha - \beta) = E(z_\alpha z_\beta)$$

is not necessarily zero.

Estimates a_i of the population parameters A_i are obtained via a least-squares fit which is particularly simple because of the orthogonality of the p's:

$$a_0 = \frac{1}{N}\sum_\alpha y_\alpha = \bar{y},$$

$$a_1 = \frac{\overline{p_1 y}}{\overline{p_1^2}} = \frac{1}{N}\sum_\alpha C_\alpha y_\alpha, \quad C_\alpha = \frac{p_1(t_\alpha)}{\overline{p_1^2}},$$

$$a_2 = \frac{\overline{p_2 y}}{\overline{p_2^2}} = \frac{1}{N}\sum_\alpha D_\alpha y_\alpha, \quad D_\alpha = \frac{p_2(t_\alpha)}{\overline{p_2^2}}.$$

The a_i are linear functions of the random variables y_α. The means and variances of these parameters are estimated as (for a_1, for example)

$$\mathrm{ave}(a_1) = \frac{\overline{p_1E(y)}}{\overline{p_1^2}} = \frac{\overline{p_1(A_0 + A_1p_1 + A_2p_2)}}{\overline{p_1^2}} = A_1$$

$$\mathrm{var}(a_1) = E(a_1 - A_1)^2 = E(a_1^2) - A_1^2$$

$$= \frac{1}{N^2}\sum_\alpha\sum_\beta C_\alpha C_\beta E(y_\alpha y_\beta) - A_1^2$$

$$= \frac{1}{N^2}\sum_\alpha\sum_\beta C_\alpha C_\beta E(z_\alpha z_\beta)$$

$$= \frac{1}{N^2}\sum_\gamma W_\gamma R(\alpha - \beta).$$

The weights W_γ depend only on the known function $p_1(t_\alpha)$ and the assumed stationarity of z has been invoked. If the $R(\alpha - \beta)$ are taken to be zero the usual result for the independent case is recovered. Similar results apply for a_2.

To apply these formula for the assessment of the trends, the estimates a_i and $\sum_\alpha W_{i\alpha}\hat{R}_\alpha$ for the population mean and variance must be used. If the statistic $(A_i - a_i)/(\sum_\alpha W_{i\alpha}\hat{R}_\alpha)^{1/2}$ is normally distributed with mean zero and variance one, as might be expected for large N, then the usual statistical significance test can be applied.

In the absence of precise knowledge of the distribution of the a_i only an estimate of the significance of the a_i's can be made. The hypothesis that A_i is zero is rejected if

$$|a_i| > 2(\sum_\alpha W_{i\alpha}\hat{R}_\alpha)^{1/2} \sim 2 \text{ std. error}$$

in analogy with a usual significant test at about the 5% level.

APPENDIX B

The Significance of Cross-Correlation Coefficients

An assessment of the significance of the sample cross-correlation coefficient is made following methods used for instance by Anderson (1976) for autocorrelations and based on some results given in Bendat and Piersol (1971).

This assessment of significance is based on an expression for the variance of the sample cross correlation for jointly Gaussian stationary random processes x, y with mean zero. The expression is a discrete form of an expression given in Bendat and Piersol (1971, pp. 181–184) for large N of the form

$$\mathrm{var}[\hat{r}_{xy}(\tau)] \approx N^{-1}\{1 + r_{xy}^2(\tau) + 2\sum_{\alpha=1}^{N-1}[r_{xx}(\alpha)r_{yy}(\alpha) + r_{xy}(\alpha+\tau)r_{yx}(\alpha-\tau)]\},$$

where $r_{xy}, r_{yx}, r_{xx}, r_{yy}$ are the population cross-correlation and auto-correlation coefficients.

To apply this formula for the assessment of the cross-correlation coefficient it is assumed that $r_{xy}(\tau) = 0$ for all τ. Sample values of r_{xx}, r_{yy} are introduced into the formula to give

$$\mathrm{var}(\hat{r}_{xy}(0)) \approx N^{-1}[1 + 2\sum_{\alpha=1}^{N-1}\hat{r}_{xx}(\alpha)\hat{r}_{yy}(\alpha)].$$

As in Appendix A, the hypothesis that $r_{xy}(0) = 0$ is rejected at approximately the 5% level if

$$|\hat{r}_{xy}(0)| > 2\{N^{-1}[1 + 2\sum_{\alpha=1}^{N-1}\hat{r}_{xx}(\alpha)\hat{r}_{yy}(\alpha)]\}^{1/2} \sim 2 \text{ std. dev.}$$

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