LOOKING FOR EVIDENCE OF CLIMATIC CHANGE IN HYDROMETEOROLOGICAL TIME SERIES

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INTRODUCTION

Analyses of hydrometeorological time series for practical purposes, for example to aid in the design of reservoirs for hydroelectric power generation, have generally assumed stationarity of the data. Similarly, climatologists have related their analyses to 30-year climate 'normals'. The most obvious exception to this assumption has occured when the effects of man on a watershed are so large as to force attention; for example, inter-watershed diversions.

Recently, considerable scientific attention has been focused on a much larger scale anthropogenic effect, the 'greenhouse warming' and it's anticipated change in climate and, hence, in water resources. Projections (e.g. Gleick, 1987) have forecast decreases in runoff of up to 50% resulting from increases in temperature of one degree Celcius.

If the induced changes are indeed magnified in hydrologic time series then by detecting trends in these series it should be possible to work backwards and identify the causative climatic change. This paper looks at two data sets: 1) long term lake levels from Africa and North America, and 2) long-term runoff and nearby precipitation and temperature data from sites across Canada. These data are analysed for important components and associated physical causes.

In a current international study (WMO, 1988), climatologists are analysing time series by looking for differences in 30-year 'normals' over the length of the time series. This assumes that 30 years is a long enough period for a mean statistic to be valid and amounts to describing climatic time series as non-stationary with local periods of stationarity.

An alternate approach is to search for significant changes in parameters within the whole record of long time series. There are two possible ways to do this; the first is to hypothesise a statistical model and see if the data samples correspond to expectations; the second is to work backwards from the data to the model. The first method may show only that simple models are inadequate to describe physical processes. The second approach can, at best, offer only one possible explanation for the observed data. But data from very dissimilar physical processes may not be distinguishable using common statistical techniques and the user may end up with the wrong model altogether.

This study follows the first approach and assumes a simple model for time series consisting of trend, periodic, autoregressive and random residual components. The trend component of a time series is generally associated with changes in the structure of the time series caused by cumulative natural or man-made phenomena. For example, the accumulation of 'greenhouse' gases in the atmosphere is said to cause a trend component in temperature and precipitation records and hence might be assumed to have an effect on hydrologic time series. Periodicities in natural time series are usually due to astronomical cycles such as the earth's rotation around the sun. Autoregressive components reflect the tendency for an event to be dependent on the magnitude of the previous event(s), a memory effect.

Time series are analysed individually; using averages may hide underlying patterns in the data. For example, Goodridge (1989) has shown that averaging mean annual temperatures over all long-term climate stations in California indicates a positive trend of 0.7 degree Celcius/100 years. However, as Goodridge points out, if the California stations are

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divided into urban and rural groups, then the urban stations still indicate an increasing temperature over time (the heat-island effect) but the rural stations show a decreasing temperature. One of the most popular diagrams used by climatic change enthusiasts shows mean annual global temperature increasing over time. The data used in such diagrams are averages from hundreds of climate stations. Do these averages also hide opposite trends?

A report by WMO (1987) includes a diagram showing May-October rainfall averaged over stations in the western Sahel. The average increases from 1890 to 1950 and then decreases sharply until 1985. The significance of such trends is diminished, however, when one sees the high correlation between the average rainfall and the number of stations used to form the average.

DATA

Two sets of data were analysed. First, water levels from large lakes in North America and Africa and, second, data from streamflow and nearby climate stations in Canada. The criteria for selecting lakes were that they be large and have a long period of record. Rivers were selected for length of record and for their location in different physiographic and climatic zones. The lake levels are for different periods. The river flows and climatic data are for the period 1916 to 1988 except for Portage La Prairie which is for 1949 to 1988.

The following time series were used:

Lake Superior at Duluth, Michigan (1918-1987).
Lake Superior at Michipicoten Harbour, Ontario (1918-1987).
Lake Erie at Cleveland, Ohio (1915-1986).
Lake Erie at Buffalo, New York (1915-1986).
Great Salt Lake, Utah (1851-1988)
Lake Victoria at Jinja, Uganda (1900-1987).

Kettle River (08NN013) and Penticton (1126150), B.C.
Bow River, Banff, (05BB001) and Banff (3050520), Alberta.
Roseau River (05OD001) and Portage la Prairie (5012320), Manitoba
Saugeen River, Port Elgin, (02FC001) and Southampton (6127887), Ontario.
St. Marys River, Stillwater, (01EO001) and Truro (8206000), Nova Scotia.

Not all the climate stations had continuous data and it was sometimes necessary to fill in missing values by using long-term monthly means or from adjacent stations using simple linear regression.

METHOD

The hypothesis is made that a time series X_t can be adequately represented by a linear additive model:

$$X_t = T_t + P_t + R_t + e_t$$

where T_t is a trend component, P_t is a periodic or cyclic component, R_t is an autoregressive component and e_t is a random residual. Such a time series can be split into each of its components in turn. Spectral analysis is used after each step to indicate the presence of any remaining components. The details of the analysis techniques used at each step are given in Kite (1989).

RESULTS FOR LAKE LEVELS

Water balance

Table 1 compares the annual water balances of the selected lakes. The data for Lake Superior are annual averages over the period October 1950 to September 1960 (IGLLB, 1974). All four components are the same order of magnitude and groundwater flow is considered to be negligible. By the time water has flowed from Lake Superior through Lakes Michigan-Huron to Lake Erie, however, the water balance has altered considerably. For Lake Erie, the overlake precipitation and evaporation, although similar to those over Lake Superior, are an order of magnitude lower than the river inflow and outflow.

Table 1

Average Annual Water Balance

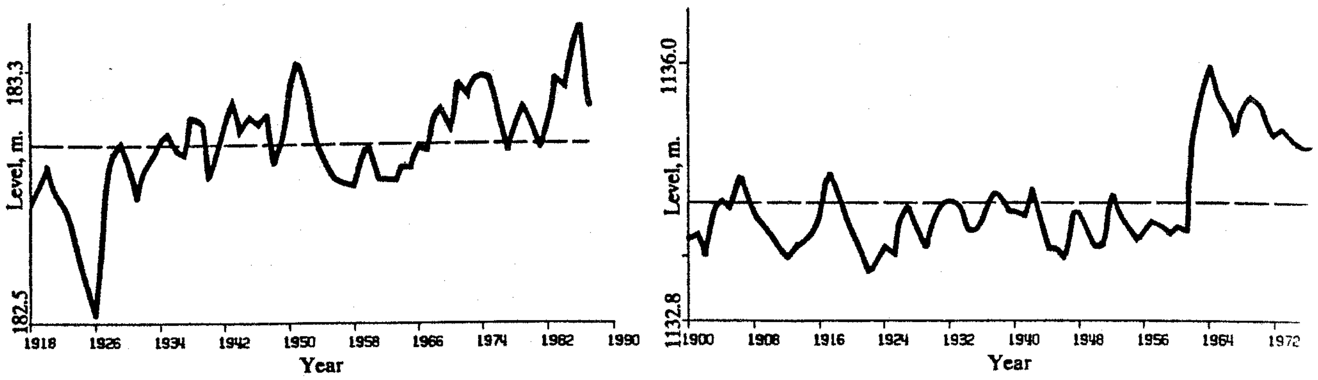
	Lake Superior	Lake Erie	Lake Victoria	Great Salt Lake
Overlake precipitation, mm.	810	860	1760	270
Overlake evaporation, mm.	560	650	1590	990
Inflow, mm over the lake	600	6600	340	720
Outflow, mm over the lake	850	7000	590	0
Basin area (land & lake, sq. km.)	210 000	104 000	264 000	57 000
Lake area (sq. km.)	82 000	27 000	68 500	6 500 (at 1283.80 m.)

Lake Victoria, the second largest fresh water lake in the world, is unusual in that the main input to the water balance is precipitation over the lake rather than river inflow and the main output is evaporation from the lake rather than river flow. The water balance components listed in Table 1 are averages over the period 1965 - 1976 (Kite, 1981).

The water balance of Great Salt Lake, Utah, is also unusual in that it has no river outflow; evaporation is the only output. The mean values of the estimated water balance components over the period 1851 - 1983 (after Stauffer, 1988) show that river inflow is the largest source of water, accounting for about 70% of the average annual water supply; precipitation over the lake accounting for the remaining 30% (Morrisette, 1988).

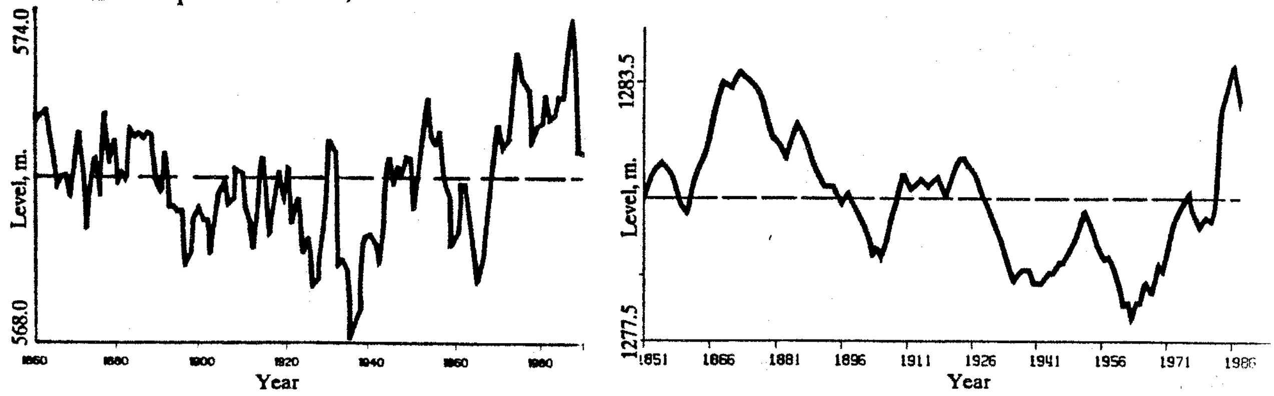
Time series analyses

Figure 1 shows the mean annual levels of Lakes Superior, Erie, Victoria and the Great Salt Lake over their historic records.



Lake Superior at Duluth, Minnesota

Lake Victoria at Jinja, Uganda



Lake Erie at Cleveland, Ohio

Great Salt Lake, Utah

Figure 1. Mean Annual Lake Levels

The level of Lake Superior as measured at Duluth shows a strong linear trend upwards. Time series analysis will provide an explanation for this. Lake Erie at Cleveland shows a downward trend until about 1940 followed by an upward trend.

The level of Lake Victoria varied within a range of only 1.2 m over the period 1900 - 1960. Then, in the early 1960's, the lake rose by about 2.5 m and then gradually fell back by about 1 m. (Kite, 1981). Although not confirmed by measurements at island stations, this rise is considered to be caused by a large increase in over-lake precipitation. Evidence exists (Nicholson, 1980) that the lake was at least as high on several occasions during the historical period. The sudden rise in the 1960's was not restricted to Lake Victoria; it also occured on Lakes Mobutu, Malawi and Tanganyika (Kite, 1981).

After a long period of decreasing water levels (1870-1960), Great Salt Lake rose by almost 6m to a high of 1283.77 m. Because of the shallowness of the lake, this resulted in an increase in surface area from approximately 2 500 km to 6 500 km and caused over $300 million in damages. To avoid further damage, water was pumped from the lake to evaporate in the nearby desert (Austin, 1988). The rise in level is wholly explained by the recorded increase in precipitation within the basin. The period 1981 to 1984 is the wettest on record and annual river inflows into the lake were 265, 330, 190 and 300 percent above average for the years 1983 to 1986 (Morrisette, 1988). Studies of the historical precipitation records have concluded (Karl & Young, 1986) that such a period of wet years has a return period of around 120 years and is a case of climatic fluctuation rather than climatic change.

The results of the time series analyses of lake data are given in Table 2.

Table 2
Time Series Components, Large Lakes

	First Order Linear Trend, %	Period-icities, %	Autoregr-ession, %	Residual %
Lake Superior at Duluth, 1918-1987	24	30	43	3
Lake Sup. at Michipicoten, 1918-1987	1	37	58	4
Duluth - Michipicoten, 1918-1987	92	3	1	5
Lake Erie at Cleveland, 1915-1986	32	14	51	3
Lake Erie at Buffalo, 1915-1986	31	14	51	3
Cleveland - Buffalo, 1915-1986	6	62	0	32
Lake Victoria at Jinja, 1900-1977	32	3	63	2
Lake Victoria at Jinja, 1900-1960	0	9	82	8
Great Salt Lake, 1851-1988	24	41	25	9

The initial spectral estimate for Lake Superior levels at Duluth over the period 1918-1987 shows a significant low frequency component (below 0.02 cycles per month, greater than 50 months period) and a significant component at a frequency of 0.08 cycles per month (one year period). The elimination of the linear trends produces a corresponding decrease in significance in the low frequency spectra. After removal of the annual cycle and the low frequency autoregressive component, only a flat spectrum remains. In terms of variance, the most significant component is autoregression, the persistence tendency of a large lake, explaining over 40% of the total variance. Next is, as might be expected, the annual cycle, explaining almost 30% of the variance. Perhaps unexpectedly, the other significant component is a linear trend explaining over 20% of the variance. This is caused by isostatic adjustment of the Great lakes region to the retreat of the last ice age around 10 000 years ago (Kite and Adamowski, 1973). Only 3% of the total variance is left unexplained as random residual.

That the linear trend is caused by isostatic adjustment can be demonstrated by taking differences between lake levels at Duluth and at Michipicoten. Differencing minimises the common components and exagerates the dissimilar components. Analysing the differences confirms that the linear trend explains over 90% of the variance leaving only 3% periodicity and 5% residual. A linear regression fitted to the trend line shows that the north shore of Lake Superior is rising at a rate of about 450 mm per 100 years relative to the southern shore.

A similar analysis for Lake Erie shows major autoregressive components and significant linear trends at both Cleveland and at Buffalo. However, when differences are analysed, the linear trend is reduced from 30% to only 6% and the periodic component increases from 14% to over 60%, completely different from Lake Superior. This is because Lake Erie is almost out of the area of isostatic rebound (Adamowski & Kite, 1973) so that linear trend along the lake is minimal. However, there is a strong seasonal cycle in the strength of the predominant south-westerly wind, inducing a seasonal difference in level along the lake.

For Lake Victoria the time series analysis over the whole period of record, 1900-1977, shows that over 30% of the total variance is due to linear trends. This is misleading and is due to the sudden rise in level over the four years 1960 - 1964, not to a gradual rise over the whole period. When a second time series analysis is carried out omitting the period of the sudden rise, then the trend variance becomes a negligible 0.29% and the most important component is seen to be autoregression.

Such a jump causes difficulty in time series analysis. Rao(1988) has discussed the use of intervention analysis but this requires the date of the jump to be identified explicitly and cannot be reliably used as a model component. Salas et al (1981) fitted an intervention model to Lake Victoria outflows including the jump but this model could not be used for because of the two different rainfall seasons (April-May and November-December) and the almost constant year-round temperature.

For Great Salt Lake the analysis shows a strong downward linear trend, a dominant periodicity and a strong autoregressive component.

RESULTS FOR RIVER AND CLIMATE STATIONS

Five rivers were selected in different areas of Canada and analysed for the same period 1916-1986. Monthly precipitation and temperature data were selected from those stations with continuous data for the same period and located as close to the river measuring sites as possible. The results of time series analysis of both sets of data are given in Table 3 and are presented graphically in Figures 2 and 3.

Table 3
Time Series Components
Selected Canadian Stations

	First Order Linear Trend, %	Periodicities, %	Autoregression, %	Residual %
Penticton, precip.	1	8	2	89
Banff, precip.	0	21	0	78
Portage La Prairie, precip.	0	47	0	53
Southampton, precip.	0	10	1	88
Truro, precip.	2	12	0	86
Kettle River	0	91	4	5
Bow River	0	95	1	4
Roseau River	0	68	14	18
Saugeen River	0	67	4	29
St. Mary's River	0	50	1	49

Figure 2. Time Series Analysis
Selected Canadian Streamflow Stations, 1916-1988

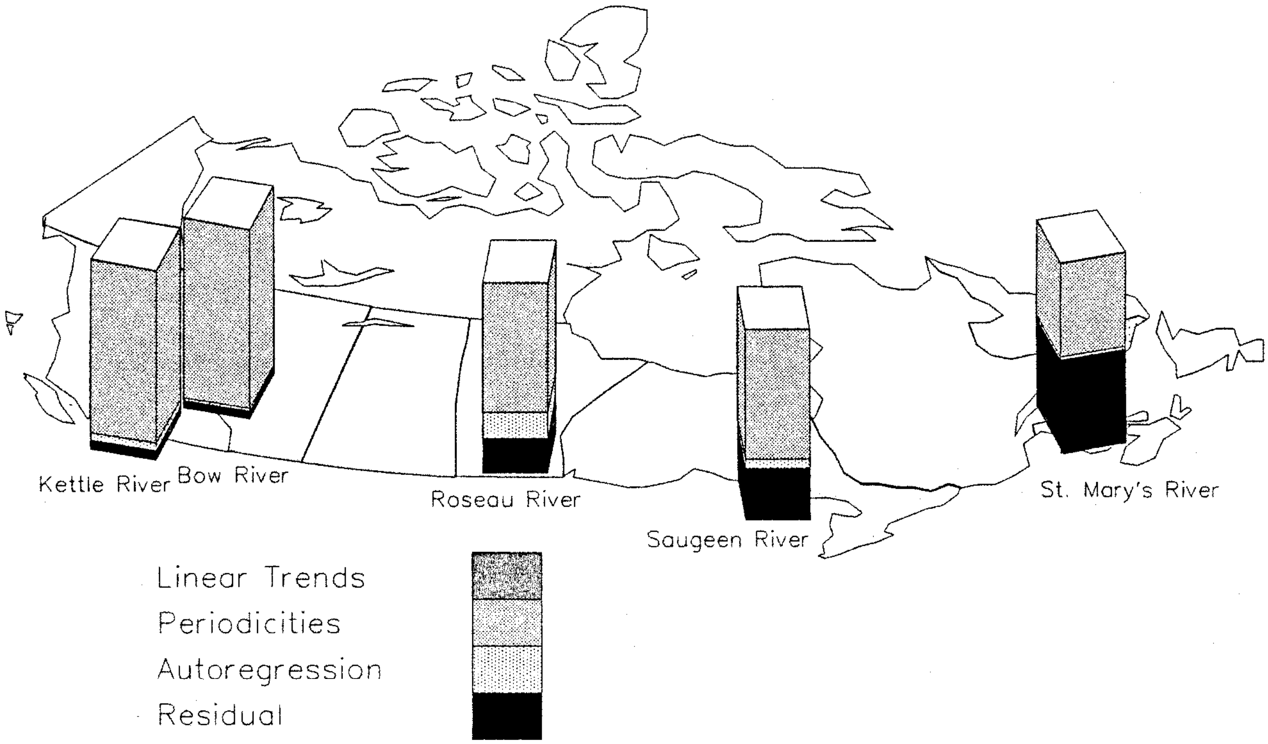
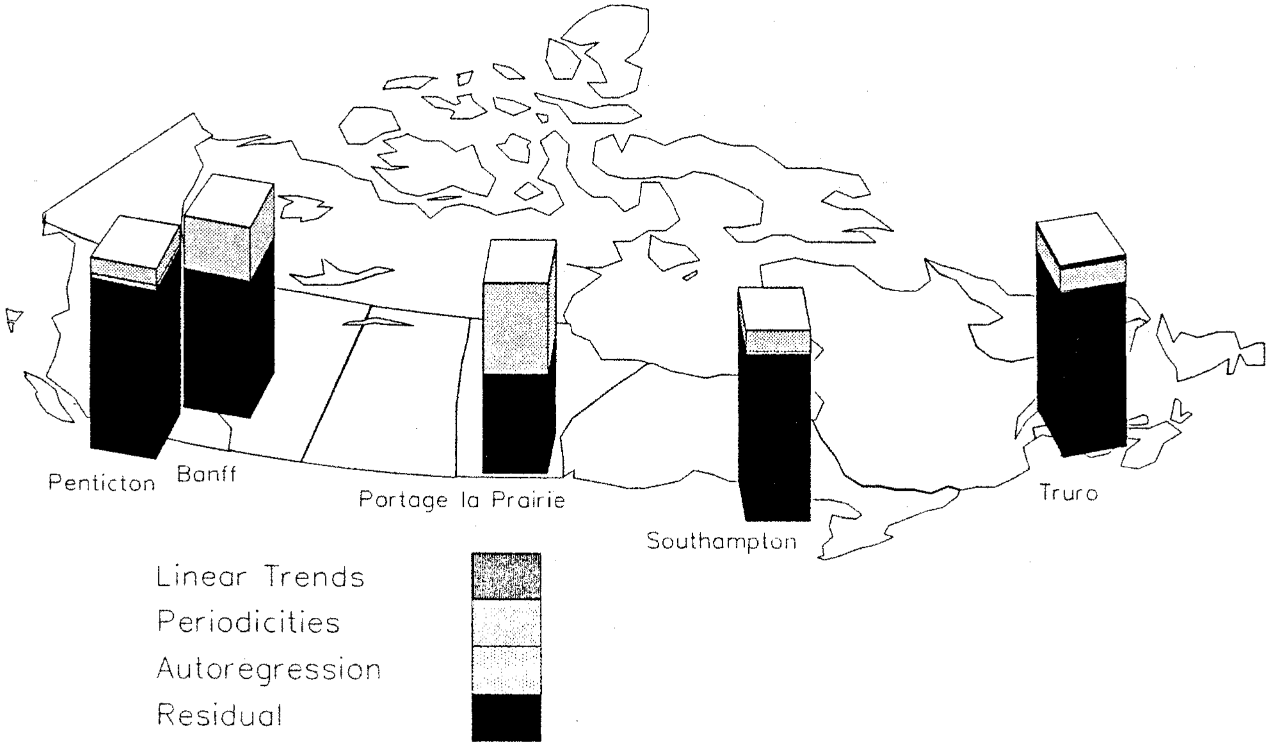


Figure 3. Time Series Analysis
Selected Canadian Precipitation Stations, 1916-1988
(except Portage la Prairie, 1949-1988)



Analysis of the temperature data showed that, at all stations, periodicity accounted for between 94 and 97% of the variance, the remainder being random residual. When the annual cycle (the major cause of the periodicity) was removed, all the temperature series showed over 90% random residual. No station showed any significant trend component.

The Kettle River, being glacier fed, shows a dominant periodic component with very low autoregression and random component. The closest precipitation station, Penticton, on the other hand, shows almost total random component with very low periodicity. The Bow River is similarly glacier fed with a single annual peak in June or July each year. The analysis confirms this impression; there are no significant trend or autoregressive components and 95% of the variance is explained by the annual cycle. Only 4% of the variance remains as unexplained residual. For comparison, an analysis of mean monthly precipitation at Banff, Alberta, shows almost 80% of the variance to be unexplained residual with only 21% explained by periodicities. The movement of water from precipitation to runoff via snow and glaciers thus removes most of the random component replacing it with periodicity.

The Roseau River in Manitoba shows a lower periodic component with a higher autoregression or persistence and a larger random component. The closest precipitation station, Portage la Prairie, is almost evenly split between a periodic component and a random residual indicating the strong cyclic distribution of prairie precipitation.

The Saugeen River, in Ontario, usually shows a single snowmelt peak in March or April but other rainfall and/or snowmelt peaks have occured in all the other months of the year except June. The analysis results in Table 3 confirm that almost 70% of the total variance is still due to the annual cycle but now almost 30% of the variance is unexplained as a random residual. The precipitation analysis for Southampton shows a small periodic component with dominant random component.

St. Marys River at Stillwater, Nova Scotia, has a much greater scatter of peak flows. There is still a preponderance of snowmelt peaks in April and almost 50% of the variance is explained by the annual component but the other 50% is unexplained residual reflecting the varied sources and occurence times of peak flows in this climatically varied area. The analysis of precipitation data from Truro confirms the largely random nature of the precipitation with only a small periodic component. A small (2%) linear trend also occurs in the Truro data.

CONCLUSIONS

Time series analysis can show the relative magnitude of components such as trends, jumps, periodicities and autoregression within climate-related time series. Any components suggested by statistical analysis must have a valid physical explanation.

There are a number of qualifications to the use of time series analysis.

1. The apparent components of a time series may change with time; what appears to be a trend now, may turn out to be part of a periodicity when looked at over a longer time span.

2. Averaging data from many stations may disguise the real components as has been illustrated with California temperature data. Varying the number of stations used in the averaging should also be avoided.

3. Jumps in the data must be accounted for, otherwise any trend analysis is misleading, as was shown with the Lake Victoria data.

Bearing these qualifications in mind, the following results have been presented:

1. The time series components found in Lake Superior levels all have physical explanations; the long term trend is due to uplift after the last ice age. Similarly the analyses of the Lake Erie data are explained by physical causes.

2. The sudden rise in Lake Victoria cannot be explained from observed data but is probably due to an unmeasured increase in precipitation over the lake.

3. The changes in level of Great Salt Lake and the apparent cyclicity are considered as within the range of historic fluctuation and are not ascribed to any modern climatic change.

4. The analyses of Canadian streamflow data show a decreasing importance of periodicities and an increasing proportion of residual variance from west to east confirming the change in source of runoff from glacier and snowmelt to mixed snow/rainfall.

5. The precipitation data all show dominant random components with only Portage la Prairie showing any significant periodicity. Only Truro shows any linear trend and this is not significant.

6. The annual cycle dominated all the temperature series; no other significant components were found.

In conclusion, an analysis of lake levels, river flows and associated climatic records has not found any components likely to be caused by 'greenhouse warming'.

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