Nordic Hydrology, 24, 1993, 135-150

Analysing Hydrometeorological Time Series for Evidence of Climatic Change

Paper presented at the 9th Northern Res. Basin Symposium/Workshop
(Whitehorse/Dawson/Inuvik, Canada – August 1992)

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Considerable scientific attention has been focused on a measured increase in atmospheric CO_2 and a suspected corresponding change in climate. Such a change in climate, if it occurred, might be expected to have a magnified effect on hydrologic time series and, indeed, projections have been made of major changes in water resources.

If the climatic changes are indeed magnified in hydrologic time series then, by detecting trends in such series, it should be possible to work backwards and identify the causative climatic change. This paper looks at two data sets: 1) long-term temperature, precipitation and streamflow data from sites across Canada and 2) long-term levels of large lakes in Africa and North America.

The study assumes that time series may be modelled by 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 manmade phenomena. 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.

The analyses of temperature, precipitation and streamflow data show some significant linear trends but no pattern is apparent. The analyses of longterm lake levels also identify linear trends but these are all explainable without invoking climate change due to greenhouse gases.

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 data analyses to 30-year climate 'normals'.

Recently, however, scientific attention has enthusiastically adapted to the idea of a changing climate. Edward Lorentz, the climatologist pioneer of chaos theory is quoted (Gleick 1987) questioning the idea of a stable climate:

> "Is there a climate? Obviously the average weather over the last 12,000 years is different than the average weather over the previous 12,000 years when most of North America was covered by ice. Is it possible that a system like the weather may never converge to an average?"

This recent interest in a changing climate is due to the concern over a suspected 'greenhouse warming' of the atmosphere and a consequent effect on our way of life.

Many studies have anticipated the effects of a doubling of radiatively-active gases on water resources. For example, Idso and Brazel (1984) estimated changes in streamflow in Arizona varying from -30% to -60% for a 10% decrease in precipitation. Wigley and Jones (1985) showed that changes in precipitation always have an amplified effect on runoff. If Γ is the runoff ratio of the basin (runoff/precipitation), α is the change in precipitation due to climatic change and β is the change in evaporation due to climatic change, then the ratio of runoff after climatic change to runoff before climatic change is

$$\frac{R_1}{R_0} \equiv \frac{\alpha-(1-\Gamma)\beta}{\Gamma} \qquad (1)$$

Γ varies between about 0.1 for rivers in arid areas to about 0.7 for rivers in humid tropical areas. From Eq. (1), a +/-10% change in precipitation over a basin with a runoff ratio of 0.2 would result in a +/-50% change in runoff, assuming no change in evaporation.

This amplification in hydrologic time series should make it easier to detect trends in these series and it should then be possible to work backwards and identify the causative climatic change. This paper looks at two data sets: 1) long-term runoff and nearby precipitation and air temperature data from sites across Canada (and a few sea surface temperature data sets), and 2) long-term lake levels from Africa and North America. These data are analyzed for important components and associated physical causes.

The study 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 manmade phenomena. 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 analyzed 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, when Goodridge divided the California stations into those in counties with more than 1 million population and those in counties with less, then, while the populous counties still indicate an increasing temperature over time (the heat-island effect), the less-populous counties show a decreasing temperature. Many papers on climatic change (*e.g.* Jones *et al.* 1986) show a diagram of mean global temperature increasing with time. The data used in such diagrams are averages from hundreds or thousands of climate stations. Do these averages also hide opposing trends?

Stations were selected for their length of record and for their location in different physiographic and climatic zones. The streamflow and climate data in the south of Canada are all for the period 1916-1986 except for Portage La Prairie which is only 1949-1988. Stations in the north of Canada have shorter periods for record. 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 by using data from adjacent stations with a simple linear regression.

Method

It was assumed that a time series X_t can be represented by a model

$$X_t = T_t + P_t + R_t \tag{2}$$

where t is time in months, T_t is a trend component

$$T_t = a_0 + a_1 t + a_2 t^2 + ,...., + a_p t^p \tag{3}$$

a_0 - a_p are coefficients, P_t is a periodic or cyclic component

$$P_t = A_0 + \sum_{k=1}^{N/2} [A_k \cos (\frac{2\pi k t}{N}) + B_k \sin (\frac{2\pi k t}{N})] \tag{4}$$

A_k and B_k are coefficients, N is the number of monthly data and R_t is a stochastic component

$$R_t == \sum_{j=0}^{k} \alpha_j R_{t-j} + \epsilon_t \tag{5}$$

where α_j are coefficients, j is the autoregressive order number and ε_t is the random residual at time t.

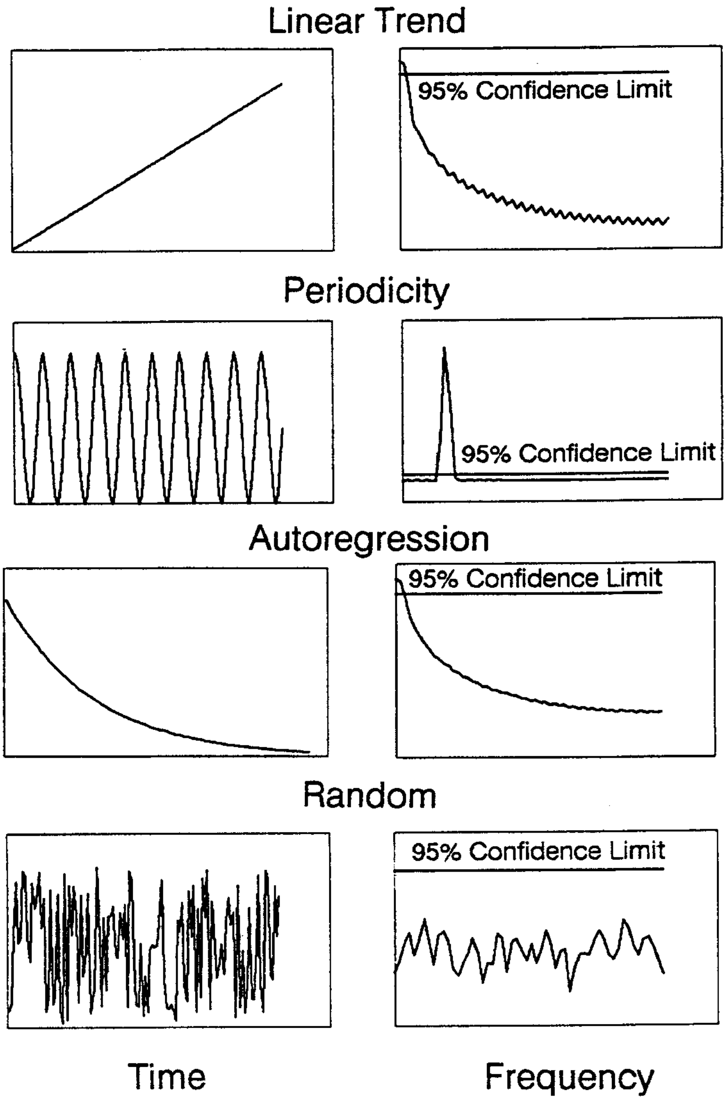

Fig. 1. Time (left-hand) and frequency (right-hand) domain plots of sample data (ordinates of right-hand graphs are log spectral density except for Periodicity which is spectral density).

Converting the data from the time domain to the frequency domain aids in detecting significant components. Fig. 1 shows examples of some common components in both time and frequency domains. The relative importance of these components can then be expressed as percentages of the total variance of the time series. Details of the analysis techniques used are given in Kite (1989).

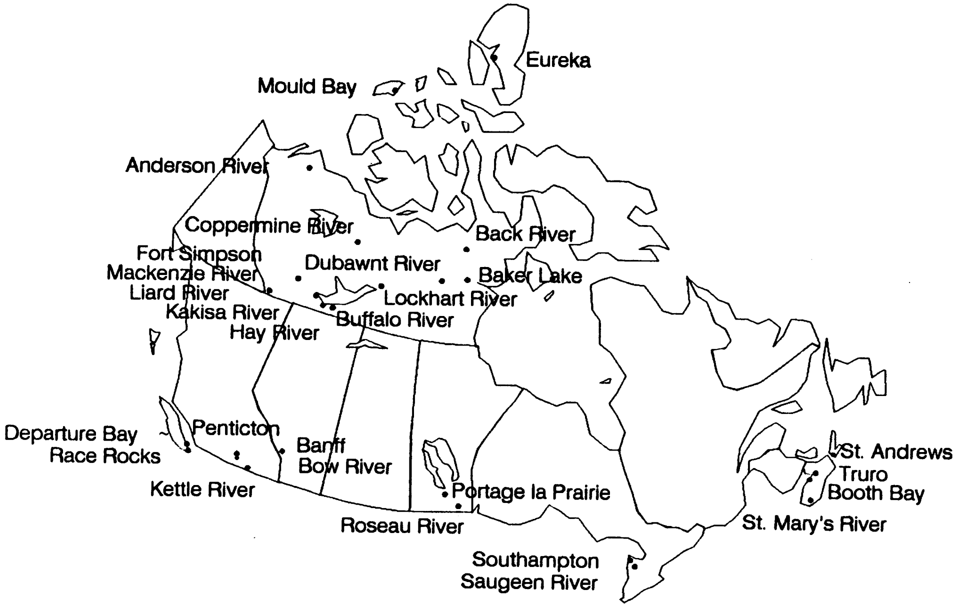

Fig. 2. Station location map.

Results

Temperature, Precipitation and Streamflow Data

Unregulated streamflow records were selected from different areas of Canada. Precipitation and temperature data were selected from stations located as close to the streamflow stations as possible (Fig. 2). The results of time series analyses of both sets of data are given in Table 1 and Figs. 3, 4 and 5. Table 1 also includes results from analyses of four sets of sea surface temperatures. The percentages in Table 1 have been rounded and do not always add up to 100%.

Analysis of the air temperature data showed that, at all stations, periodicity accounted for between 93 and 97% of the variance, the remainder being random residual. The sea surface temperatures also show very high periodicities but show some small (2-8%) autoregressive components, reflecting the higher heat content and temperature stability of the water. When the annual cycle (the major cause of the periodicity) was removed, all the temperature series showed over 90% random residual.

The results of the analyses of the precipation data may be considered at the same time as those of the streamflow series. 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

Table 1 – Time series components as percentage of total variance for Canadian temperature, precipitation and streamflow data.

	Trend	Periodicities	Autoregression	Residual
Air Temperature				
Penticton, 1916-88	0	95	0	4
Banff, 1916-88	0	93	0	6
Portage La Prairie, 1916-88	0	96	0	3
Southampton, 1916-88	0	95	0	4
Truro, 1916-88	0	96	0	3
Baker Lake, 1950-89	0	97	0	2
Eureka, 1948-89	0	97	0	2
Ft. Simpson, 1930-89	0	96	0	3
Mould Bay, 1949-89	0	97	0	2
Sea Temperature				
Departure Bay, 1915-90	0	96	1	3
Race Rocks, 1921-90	0	86	8	6
Boothbay, 1906-90	0	93	2	3
St. Andrews, 1921-90	0	96	2	1
Precipitation				
Penticton, 1916-88	1	8	1	88
Banff, 1916-88	0	21	0	78
Portage La Prairie, 1949-88	0	47	0	52
Southampton, 1916-88	0	28	1	71
Truro, 1916-88	2	11	0	86
Baker Lake, 1950-89	2	57	1	38
Eureka, 1948-89	0	55	0	44
Ft. Simpson, 1927-89	0	33	0	66
Mould Bay, 1949-89	1	58	0	40
Streamflow				
Kettle River, 1916-86	0	91	3	4
Bow River, 1916-86	0	94	1	3
Roseau River, 1916-86	0	90	4	5
Saugeen River, 1916-86	0	68	4	26
St. Mary's River, 1916-86	0	49	1	48
Anderson River, 1970-88	0	87	4	7
Back River, 1965-88	0	92	1	6
Buffalo River, 1969-88	2	77	12	7
Coppermine River, 1967-88	0	83	11	4
Dubawnt River, 1969-88	5	73	13	7
Hay River, 1966-88	0	78	6	15
Kakisa River, 1964-88	2	55	32	10
Liard River, 1966-88	0	93	1	5
Lockhart River, 1967-88	0	57	37	4
Mackenzie River, 1965-88	0	93	2	3

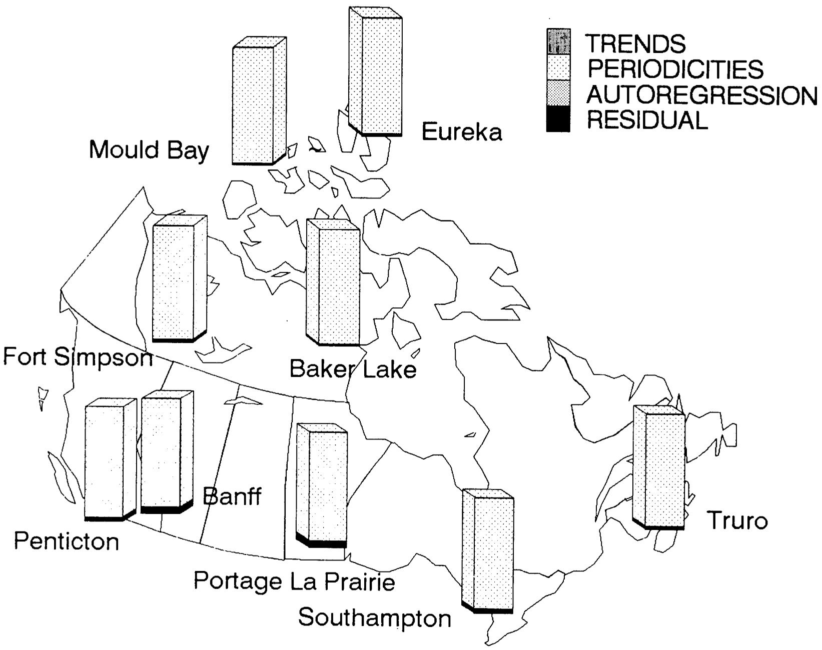

Fig. 3. Time series components (% of total variance) for air temperature data.

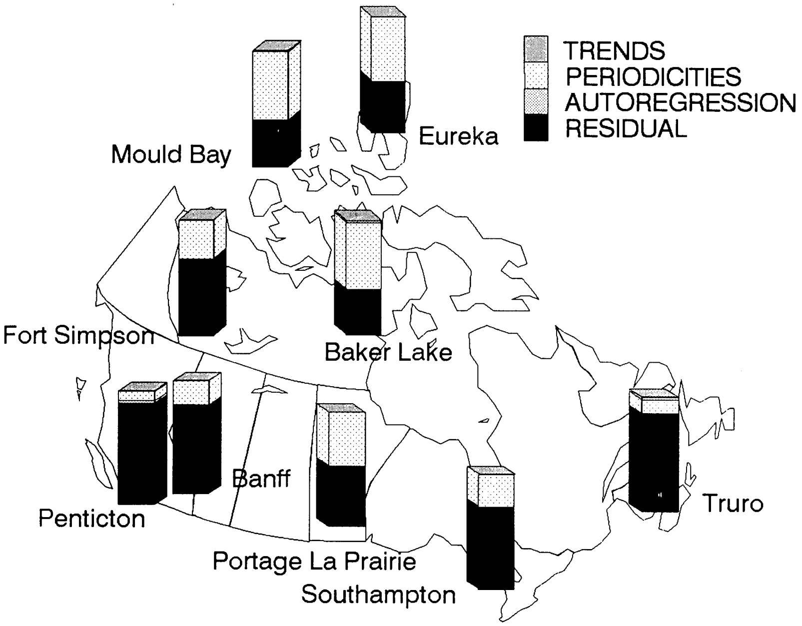

Fig. 4. Time series components (% of total variance) for precipitation data.

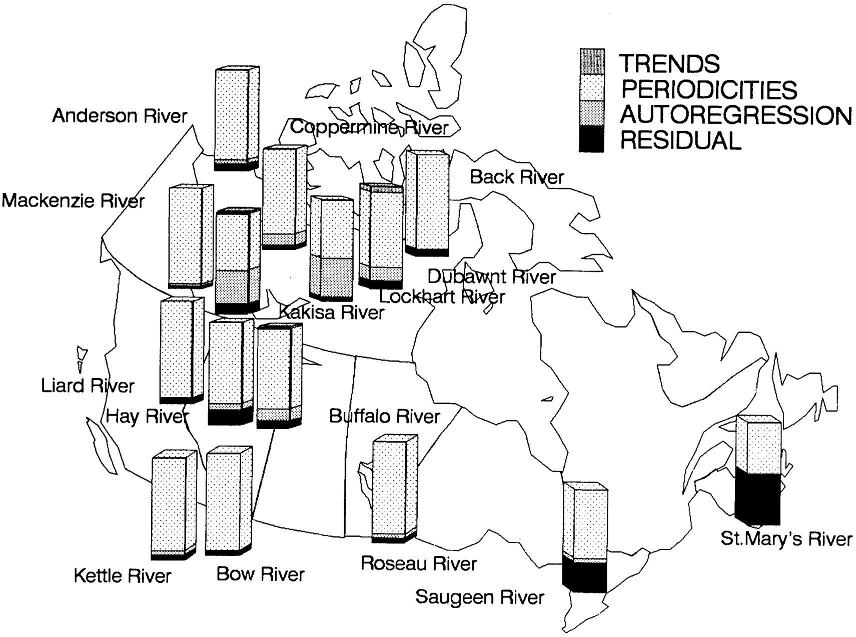

Fig. 5. Time series components (% of total variance) for streamflow data.

glacier fed with a single annual peak in June or July each year; 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 storage effect of the catchment and the interception damp the random component in the precipitation and introduce a periodic component due to the annual temperature cycle.

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 snow-melt peak in March or April but other rainfall and/or snowmelt peaks have occurred in all the other months of the year except June. The analysis results in Table 1 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. Mary's 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 occurrence 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.

The data from northern Canada are much more varied, perhaps because of the shorter periods of record available for analysis. The northern rivers have more significant autoregression components and several have trend components. The corresponding precipitation data show an even split between periodicity and random residual (for example, precipitation at Ft. Simpson shows a 33% periodicity while streamflow in the Mackenzie River at Ft. Simpson shows a 93% periodic component). Those rivers with significant autoregressive components (Kakisa, Lockhart) have lakes occupying large proportions of their drainage areas.

The measured increase in CO_2 since industrialization may be fitted by an exponential curve. However, it is not known what form of relationship the supposed climatic change resulting from this may have in terms of changes in observed temperature, precipitation or streamflow. As an initial step, however, a first order linear trend might be a useful indicator, at least over a short time period. A pattern of significant linear trends might provide an indication that some form of climatic change was occurring. Table 2 shows the intercepts and slopes for first order linear trends fitted to all the data sets as well as indicating those that are significant at the 5% level in an F test. The slopes are in units of °C/month for temperature, mm/month for precipitation and m^3/s/month for streamflow. None of the first order linear trends in the air temperatures are significant but two of the sea surface temperature trends are significant, one on each coast.

Several of the precipitation and streamflow data sets have significant trends, their locations and magnitudes are shown in Fig. 6, but no pattern is apparent. This confirms findings by Gan (1992) that warming and cooling trends in North America are seasonal and regional and that both phenomena can take place at the same location during different seasons.

Lake Levels

Monthly lake levels for Lake Superior at Duluth and at Michipicoten, Lake Erie at Cleveland and at Buffalo, Great Salt Lake near Salt Lake City and Lake Victoria at Jinja were analyzed for time series components. The locations are shown in Fig. 7 and the results are given in Table 3.

The spectral estimates of monthly Lake Superior levels at Duluth for the period 1918-1987 shows autoregression, the persistence tendency of a large lake, explaining over 40% of the total variance and periodicity explaining another 30%. 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

Table 2 – Intercept, slope and significance of first order linear trends.

	Intercept	Slope	Signif. at 5% ?
Air Temperature			
Penticton	1.3	+0.0039	N
Banff	– 28.0	+0.016	N
Portage La Prairie	– 46.0	+0.025	N
Southampton	– 4.2	+0.005	N
Truro	– 6.2	+0.0061	N
Baker Lake	– 43	+0.016	N
Eureka	14	−0.017	N
Ft. Simpson	– 32	+0.014	N
Mould Bay	– 40	+0.011	N
Sea Temperature			
Departure Bay	– 2.5	+0.007	N
Race Rocks	5.9	+0.0033	Y
Boothbay	– 18	+0.0091	Y
St. Andrews	– 20	+0.010	N
Precipitation			
Penticton	– 160	+0.092	Y
Banff	62	−0.012	N
Portage La Prairie	– 180	+0.11	N
Southampton	290	−0.11	N
Truro	– 460	+0,28	Y
Baker Lake	– 490	+0.26	Y
Eureka	– 85	+0.046	N
Ft. Simpson	– 190	+0.11	Y
Mould Bay	– 180	+0.098	Y
Streamflow			
Kettle River	– 290	+0.19	N
Bow River	72	−0.017	N
Roseau River	90	−0.040	N
Saugeen River	– 53	+0.056	N
St. Mary's River	– 120	+0.085	N
Anderson River	7700	−3.8	N
Back River	– 10000	+5.5	N
Buffalo River	– 3100	+1.6	Y
Coppermine River	– 1000	+0.56	N
Dubawnt River	– 11000	+5.6	Y
Hay River	– 2800	+1.5	N
Kakisa River	– 1700	+0.87	Y
Liard River	– 26000	+14	N
Lockhart River	– 440	+0.28	N
Mackenzie River	– 2700	+17	N

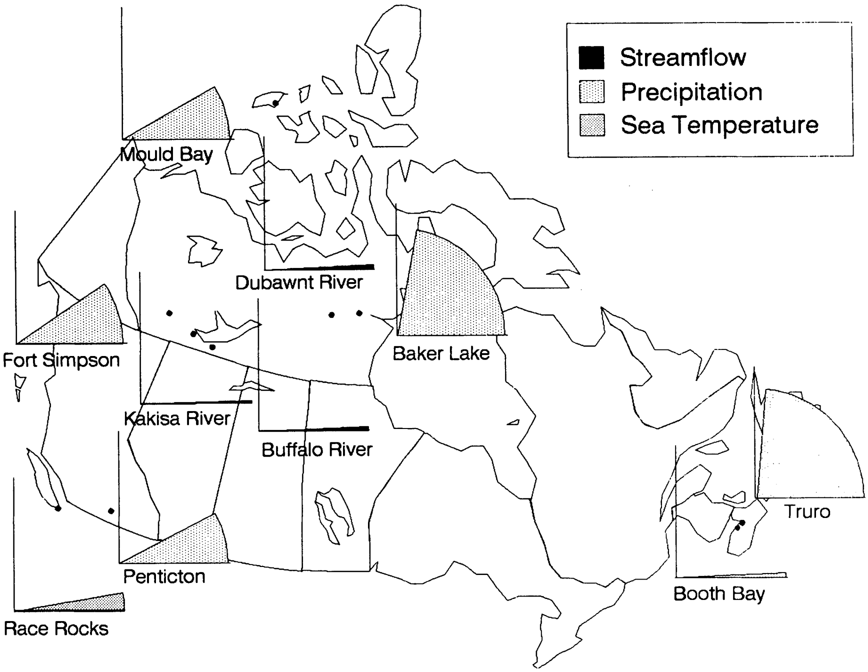

Fig. 6. Location and relative magnitudes of significant linear trends.

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 minimizes the common components and exaggerates the dissimilar components. Analyzing 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 analyzed, 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 and 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. The real lack of significant linear trend is further pointed out by the analysis at Cleveland over the full period of record, 1860-1989.

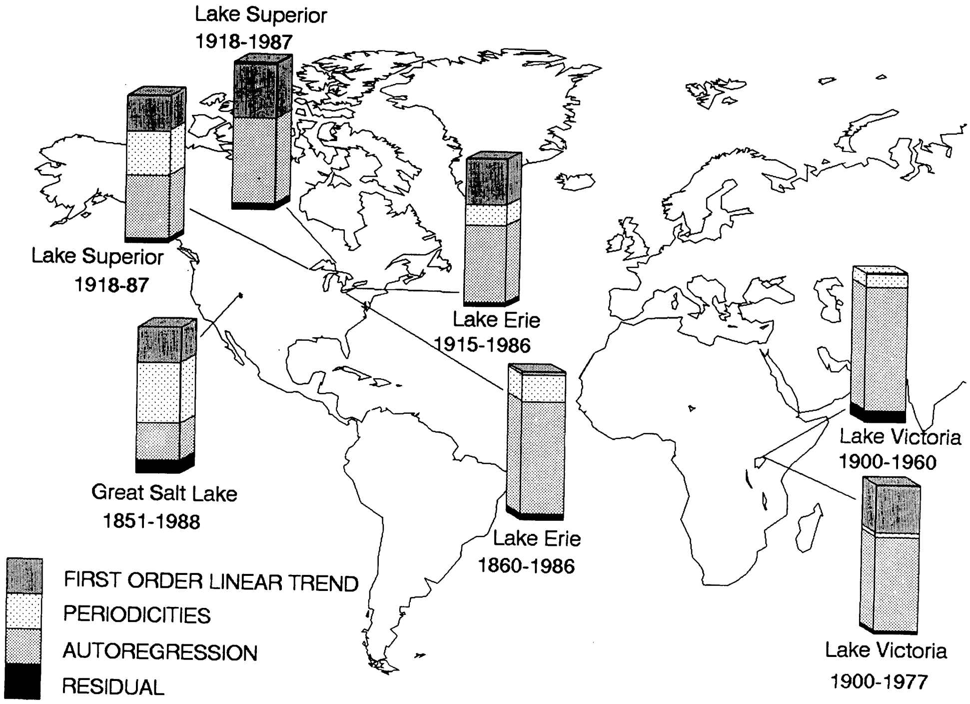

Fig. 7. Times series analysis for levels of large lakes.

Table 3 – Time series components as percentage of total variance for mean monthly lake levels.

	Trend	Periodi-cities	Autore-gression	Residual
Lk. Sup., Duluth, 1918-1987	24	30	43	3
Lk. Sup., Mich., 1918-1987	1	37	58	4
Duluth – Mich., 1918-1987	92	3	1	5
Lk. Erie, Clev., 1860-1989	2	18	76	4
Lk. Erie, Clev., 1915-1986	32	14	51	3
Lk. Erie, Buffalo, 1915-1986	31	14	51	3
Cleveland – Buffalo, 1915-1986	6	62	0	32
Great Salt Lake, 1851-1988	24	41	25	9
Lk. Vic., Jinja, 1900-1977	32	3	63	2
Lk. Vic., Jinja, 1900-1960	0	9	82	8

For Great Salt Lake the analysis shows a strong downward linear trend, a dominant periodicity and a strong autoregressive component. After decreasing for the period 1870 to 1960, Great Salt Lake rose by almost 6 m to a high of 1283.77 m. This rise in level is wholly explained by the recorded increase in precipitation within the basin (Morrisette 1988). Studies of the historical precipitation records have concluded (Karl and Young 1986) that such a sequence of wet years has a return period of around 120 years and is a case of climatic fluctuation rather than climatic change.

The time series analysis of Lake Victoria levels for 1900-1977 shows that over 30% of the toal variance is due to linear trends. However, this is misleading and is due to a sudden rise in level over the four years 1960-1964 (Kite 1981), 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.

Although not confirmed by measurements at island stations, the 2.5 m rise in level in the 1960's is considered to be caused by a large increase in over-lake precipitation and also occurred at the same time on Lakes Mobutu, Malawi and Tanganyika (Kite 1981). Evidence exists (Nicholson 1980) that the lake was at least as high on several occasions during the historical period. 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 1960's jump but this model could not be used for practical forecasting. Periodicities are of lower importance for Lake Victoria levels because of the two different rainfall seasons (April-May and November-December) and the almost constant year-round temperature.

Conclusions

Considerable resources are being spent on identifying the impacts of possible climatic changes in different regions and on different activities, *i.e.* the impact of global warming on downhill skiing (Environment Canada 1988a) and on lawn watering (Environment Canada 1989) in Quebec and on the golfing industry in Ontario (Environment Canada 1988b). Given the uncertainties in the projected climatic change scenarios, there is a case for balancing the resources spent on such impact studies by intensifying research into the search for present-day evidence of climatic change. There are many questions to be answered about the suitability of existing techniques and the number of data needed to identify any changes detected as well as a need to develop new techniques and identify suitable statistical tests. Time series analysis is one technique which can help in the search for evidence of climatic change by defining the relative magnitude of components such as trends, periodicities and autoregression within data sets. Any components suggested by such statistical analysis should then be examined for their physical causes.

The data sets analyzed in this paper have shown that a number of difficulties should be borne in mind when using 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.
3) Jumps in the data must be accounted for. Otherwise any trend analysis is misleading, as was shown with Lake Victoria levels.

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

i) The annual cycle dominated all the temperature data series studied; no other significant components were found.
ii) The analyses of Canadian precipitation and streamflow data showed several time series with first order linear trends significant at the 5% level but with no apparent pattern in the distribution of the significant stations.
iii) The time series components found in the long-term levels of large lakes all have physical explanations. The linear trends in the Great Lakes are due to isostatic rebound from the last ice age, the increase in Great Salt Lake was caused by measured heavy precipitation and the jumps in the levels of East African lakes in the 1960's are thought to be due to a large increase in rainfall.

An analysis of 36 time series of lake levels, river flows and associated climatic data has not found any pattern of trends likely to be caused by 'greenhouse warming'. The linear trends in streamflow, when converted to mm over the watersheds, were found to be less significant than those trends found in climatic data. This may indicate that changes in evaporation/evapotranspiration are greater than changes in precipitation or that the trends found are not due to climatic change at all but to some unrelated factor.

Further analyses are needed using seasonal data but avoiding the problem of unequal-length months and concentrating on those areas where current theory indicates that maximum climatic changes may be expected.

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First received: 25 September, 1992
Revised version received: 8 February, 1993
Accepted: 10 March, 1993

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