Short Term Fluctuations of Lake Erie Water Levels and the El Niño/Southern Oscillation

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This study assesses the relationship between short term fluctuations of Lake Erie water levels and the El Niño/Southern Oscillation (ENSO) using data collected from May 1978 to May 1997. After standardizing the collected data, graphical and Box-Jenkins time series techniques are utilized to assess the temporal interrelationship of the Southern Oscillation Index and Lake Erie water level variables. The statistical results demonstrate that a first-order autoregressive model AR(1) provides the best fit for the data sets of the analyzed variables. Both the graphical and statistical results suggest that short term Lake Erie water levels are fluctuating in response to the two ENSO phases, El Niño and La Niña. Negative values of the Southern Oscillation Index are related to higher lake levels while positive values are associated with lower lake levels.

Keywords: El Niño, La Niña, ENSO, Southern Oscillation, lake levels

Since 1978, a research team from the University of Windsor has been engaged in a program to monitor shoreline change and lake levels along the northern shore of Lake Erie. An analysis of the time series of shoreline and lake level data demonstrates a dynamic linkage between lake levels and shoreline behaviour. With lake level fluctuations associated with either an aggradation or retreat of the shoreline, it was decided to advance an explanation for the lake level fluctuations demonstrated in Figure 1. The graph clearly shows that lake levels rose from 174.0 metres in November 1978 to a high of 175.3 metres in May 1986, and had declined to 174.1 metres by November 1988. Between May 1989 and November 1991, they fluctuated around a mean value of 174.6 metres. Lake levels have remained above 174.5 metres since 1992, and by 1997 they attained a height of 175.1 metres.

A number of explanations have been proposed to account for fluctuations of Lake Erie water levels, including the effects of precipitation, evaporation, water inflows and outflows, and consumptive use of water (Quinn 1978; Quinn and Guerra 1986). The primary objective of this paper is to determine whether lake levels in the short term are also fluctuating in response to the El Niño/Southern Oscillation (ENSO). The research utilized a time series (1978-1997) of data on Lake Erie water levels (LEWL) and the Southern Oscillation Index (SOI). Although LEWL and SOI data have been obtained for the period of 1918 to the present, this paper analyzed only the data from May 1978 to May 1997, because this is the period during which the University of Windsor investigated the impacts of fluctuating lake levels on the beaches and shoreline of northern Lake Erie. It is worthwhile to concentrate on the LEWL and SOI data from the past twenty years because, as Trenberth and Hoar (1996) reported, the low frequency variability and the negative trend in the SOI in recent decades have been quite unusual. The climatic and hydrologic impacts of ENSO events in the past twenty years have been relatively severe because "the tendency for more frequent El Niño events and fewer La Niña events since the late 70s has been linked to decadal changes in climate throughout the Pacific basin" (Trenberth and Hoar 1996, 57). These authors reported that the recent warm trend related to El Niño in the tropical Pacific from 1990 to June 1995 has been the longest on record since 1882. Obtaining greater insights on the short term relationship between lake levels and ENSO events will enhance decision making not only in the implementation of better shore protection strategies, but also in the management of water supplies and wetland habitats.

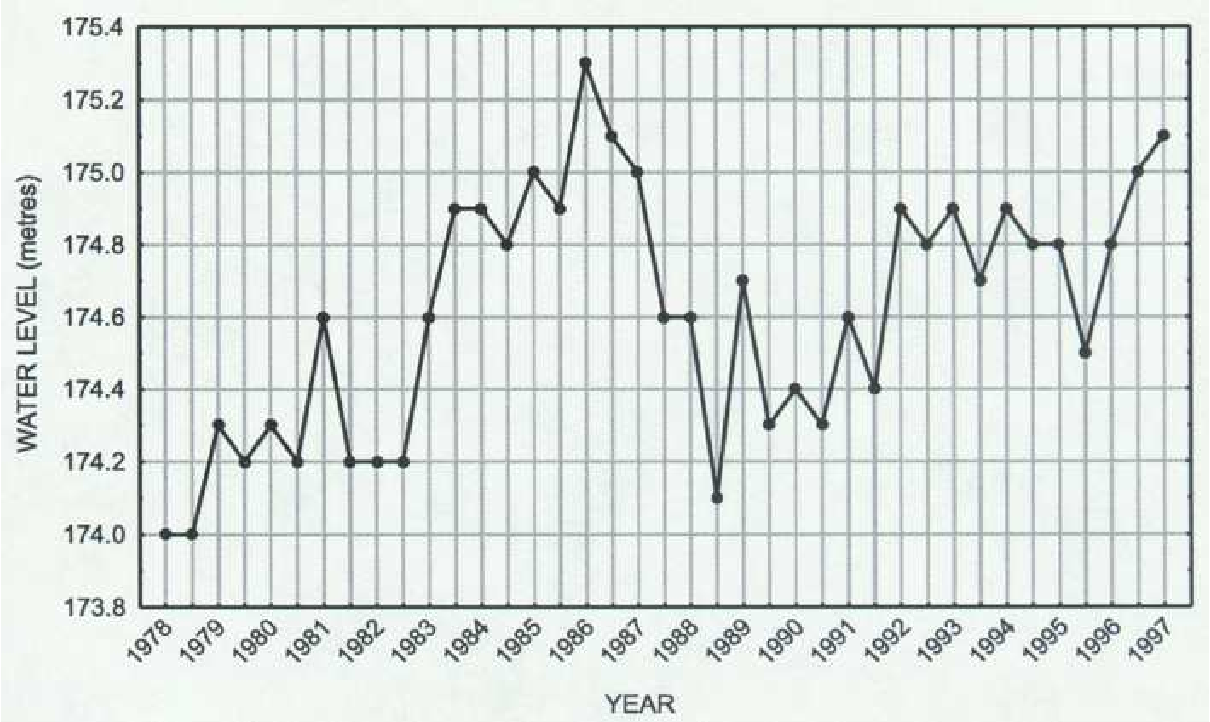

Figure : 1 Lake Erie water level fluctuations, May 1978 to May 1997.

Research Rationale

This research is premised on the rationale that ENSO may be forcing mechanisms on the atmospheric systems that govern air temperature and precipitation patterns that influence short term lake level dynamics. ENSO refers to the general system that comprises both the warm (El Niño phase) and cold (La Niña phase) sea surface temperature extremes of Walker's Southern Oscillation. A measure of the state of the Southern Oscillation is defined by the Southern Oscillation Index (SOI), which is based on the standardized sea-level pressure difference between Tahiti and Darwin, Australia (Diaz and Kiladis 1992). When the SOI is negative, the tropical Pacific is usually in its warm (El Niño) phase and, when it is positive, the tropical Pacific is usually in its cool (La Niña) state.

From the historical record it is known that ENSO events vary considerably in period and amplitude, and have different climatic impacts (Bradley and Jones 1992; Quinn and Neal 1992). With an El Niño event, it is expected that there will be higher than normal winter temperatures and precipitation in those mid-latitude locations controlled by westerly wind systems (Philander 1990). ENSO strongly influences regional and global variations in precipitation patterns (see for example, Ropelewski and Halpert 1986, 1989; Andrade and Sellers 1988; Kiladis and Diaz 1989; Hastenrath and Greischar 1993; Stone et al. 1996; and Kane 1997). Of particular significance is the study by Shabbar et al. (1997), which analyzed Canadian precipitation data from 1911 to 1994 and found significant correlations between SOI values and the observed precipitation anomalies over southern Canada. Since there are known relationships between ENSO, surface hydrology and net basin supplies (Redmond and Koch 1991; Cayan and Webb 1992; Bell and Janowiak 1995), it can be assumed that ENSO-generated variations in precipitation will influence the water level dynamics of Lake Erie in the short term. However, it is expected that a modest lag interval will exist between the initiation of El Niño or La Niña and major changes in temperature and precipitation patterns. This would also create a measurable lag interval between the initiation of an El Niño or La Niña event and significant high or low water levels.

Methods

Data Acquisition

The May 1978 to May 1997 semi-annual (May and November of each year) LEWL data used in this paper were collected by the Canadian Hydrographic Service from the Kingsville Gaging Station, located on the northern shore of Lake Erie, Canada (Environment Canada 1997). A time series (1978-1997) of the SOI was obtained from the Climatic Research Unit at the University of East Anglia. The form of the Index used in this study is defined as the sea-level air pressure difference between Tahiti, and Darwin, Australia, divided by the standard deviation of these differences and multiplied by 10 (Troup 1965). An event is considered to be related to El Niño when this Index is significantly less than zero for a period of several months, and to La Niña when the SOI is significantly greater than zero for several months. Although there is not a perfect one-to-one correlation between observed El Niño events and the SOI, the relationship has been found to be very strong (Glantz 1996).

Data Analysis

To compare the serial dynamics of LEWL with the SOI, the data were standardized to remove the effects of the different units of measurement present in the variable set, and to convert each variable into a dimensionless parameter. The data were converted to standard scores (z) using the formula:

$$z = (X - \mu) / \sigma$$

where X is a variate score, μ is the data mean, and σ is the standard deviation. In this paper the standardized Lake Erie water level data will be referred to as SLEWL, and the values of the standardized SOI will be referred to as SSOI.

After graphing the standard values of SSOI and SLEWL, Box-Jenkins time series techniques were used to analyze the temporal behaviour of the variables SLEWL and SSOI, and their temporal interrelationships with each other. Box-Jenkins ARIMA (autoregressive integrated moving average) models assume that a time series is stationary. According to Richards (1979) and Chatfield (1985) a stationary time series has the following properties: a) a constant mean, implying that there is no significant secular trend; b) homogeneity of variance, which can be evaluated by using a test for homogeneity of variance; c) no significant deterministic periodic movements or seasonal effects, and; d) an autocorrelation function (depicted on correlograms) dependent on lag interval and not on the starting position in the time series.

Since the SLEWL and SSOI data were tested and found to be stationary, this paper utilized the time series procedures which have been discussed by Chatfield (1985). They involve: 1) constructing correlograms depicting serial autocorrelation coefficients on one axis and their corresponding lag intervals on another for the variables SLEWL and SSOI; 2) producing partial correlograms depicting the partial autocorrelation coefficients for each of the variables (SLEWL and SSOI) at each lag interval; 3) examining the observed configurations in the correlograms and partial correlograms in order to fit the data to either an autoregressive model or a moving-average model. It should be noted that the data may not conform to the requirements of any model; 4) testing the residuals from the fitted models for serial autocorrelation on correlograms. This is done to assess the goodness-of-fit of the applied models; 5) treating those sets of residuals that are found to be unautocorrelated as random variables, and cross-correlating them with each other at a number of lag intervals in order to portray any temporal relationships that may exist between them.

To facilitate interpretation of obtained time series results, it should be noted that, in ARIMA modelling, the most basic tool is the correlogram depicting lag intervals on one axis and the corresponding autocorrelation coefficients on the other. Basically, the autocorrelation coefficient is like a common correlation coefficient, except that it measures the strength of the relationship between values of a time series separated by a set time interval called a lag. The line connecting the autocorrelation values for each lag describes the autocorrelation function (ACF). On a correlogram there are two dashed lines running parallel to the axis containing all of the points where the autocorrelation coefficient is zero. These are called the five percent (5%) confidence bands, and any autocorrelation coefficient falling outside of these bands is considered to be significantly greater or less than zero at the 0.05 level.

Once the appropriate model is fit to the time series data, the goodness-of-fit can be ascertained using the Box-Ljung Q statistics (see StatSoft Inc. 1997). Basically, it is necessary to extract the residuals from each of the models fitted to the analyzed data, and then construct correlograms of the autocorrelations found in the residuals. The probability values associated with the Q statistics are printed on the correlograms presented in this paper. When working at the 0.05 significance level, if any Q statistic is less than 0.05, the null hypothesis that absolute values of the autocorrelation coefficients are not significantly different from zero has to be rejected. If a model is to be considered to be adequate, then the probabilities associated with the Box-Ljung Q values must be greater than 0.05.

Results and Discussion

The graph of the values of the standardized Southern Oscillation Index (SSOI) and the standardized Lake Erie water levels (SLEWL) (Figure 2) reveals four distinctive SSOI troughs, each having negative values of less than -1.4. There are also two peaks with SSOI values greater than 1.4. Based on several studies (for example, Nicholls 1993; Bell and Janowiak 1995) that plotted SOI values, it is reasonable to claim that positive values of SSOI are related to La Niña events and negative values to El Niño events. Therefore, negative SSOI values less than -1.4 are considered to reflect El Niño events, and SSOI values greater than 1.4 La Niña events (Figure 2). Here it must be emphasized that the four El Niño events shown in Figure 2 substantiate Suplee's (1999) observations that four of the strongest El Niño events of this century have occurred since 1980.

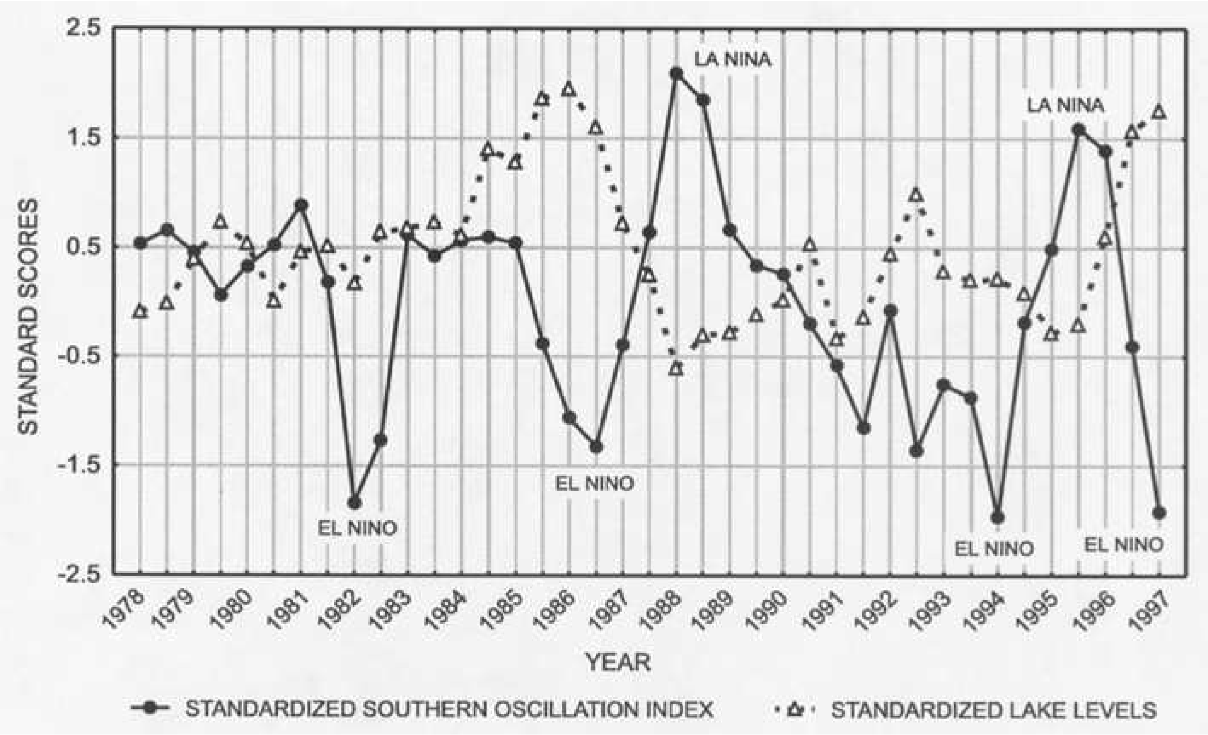

Figure 2: Standardized Southern Oscillation Index and standardized lake levels

The observed inverse relationship shown in Figure 2 is significant because the negative values of the SSOI are related to higher lake levels, while the positive values are associated with lower lake levels. Each of the higher water level peaks can be attributed to El Niño events which tend to promote higher than normal mean basin water supplies. The La Niña events, with drier conditions, seem to produce lower lake levels.

The statistical nature of the relationships between the variables SSOI and SLEWL were determined using the Box-Jenkins procedures described above. The results, obtained by using the SSOI and SLEWL data in the time series modules of the Statistica software (StatSoft Inc. 1997), clearly highlight the appropriateness of Box-Jenkins ARIMA modelling procedures that place emphasis on the recent past rather than the distant past. Without providing a detailed description of all the Box-Jenkins time series results, it is, nevertheless, worthwhile to emphasize that a first-order autoregressive model AR(1) provides the best fit for the SLEWL data set. The correlogram depicting the autocorrelation function of the SLEWL data (Figure 3) demonstrates that the ACF declined from significant autocorrelations at lag one, to insignificant autocorrelations at lags greater than one. When the residuals from the AR(1) model were subjected to autocorrelation analysis, and a correlogram (Figure 4) of the error terms or residuals was constructed, no significant autocorrelations were observed. The probabilities associated with the Box-Ljung Q statistics were all quite high, indicating no significant autocorrelation in the set of residuals. These results emphasize that the AR(1) model is the best choice to describe the serial behaviour of Lake Erie water levels. Evidently, the standardized Lake Erie water level movements seem to be associated with a long memory stochastic process.

A first order autoregressive model AR(1) was also found to provide the best fit for the data set when the SSOI data were subjected to Box-Jenkins time series analysis. The model showed that the correlogram of the SSOI data (Figure 5) decayed to non-significant levels at lags greater than one. Figure 6, a plot of the residuals from the AR(1) model, demonstrates that all of the autocorrelations fall inside of the 5 percent confidence bands, and that all of the probabilities (p) associated with the Box-Ljung Q statistics are greater than 0.05. These results support the AR(1) model as being an adequate descriptor of SSOI serial behaviour.

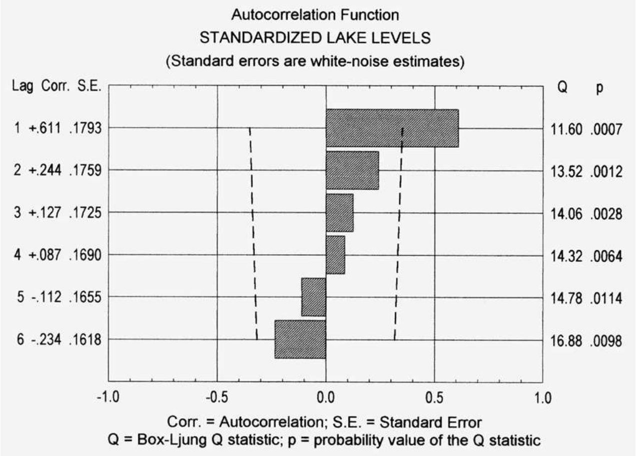

Figure 3: Correlogram of standardized Lake Erie water levels.

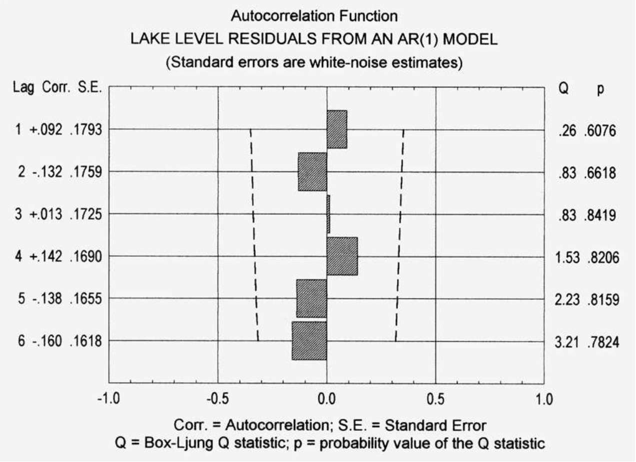

Figure 4: Correlogram of the standardized Lake Erie water level residuals from AR(1) model.

After the SLEWL data and SSOI data were fitted to AR(1) models, their residuals were cross-correlated to see which of the lag intervals yielded significant cross-correlations. Figure 7 illustrates a cross-correlogram describing the serial relationships between the SLEWL residuals from the AR(1) model and the SSOI residuals from an AR(1) model. Since there is a significant, moderately strong, inverse cross-correlation (r = -0.563) at lag one (i.e., six months), it can be claimed that lake levels have responded to El Niño events by rising and La Niña events by falling. Also, the square of the cross-correlation coefficient at this lag of six months is

0.317, thereby indicating that after the effects of the AR(1) processes have been filtered out, 31.7 percent of the serial variation in SLEWL can be accounted for by values of the SSOI.

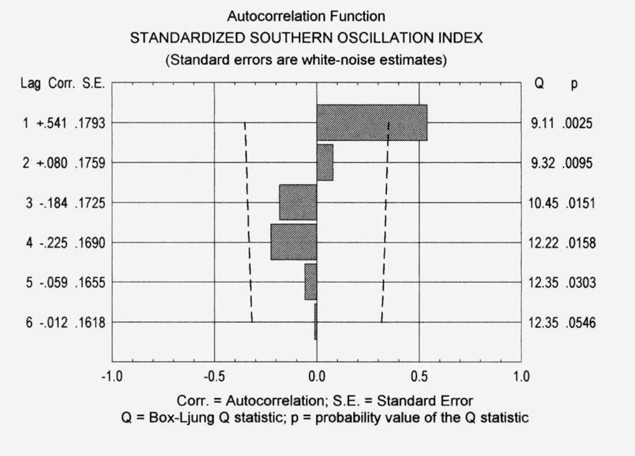

Figure 5: Correlogram of standardized Southern Oscillation Index.

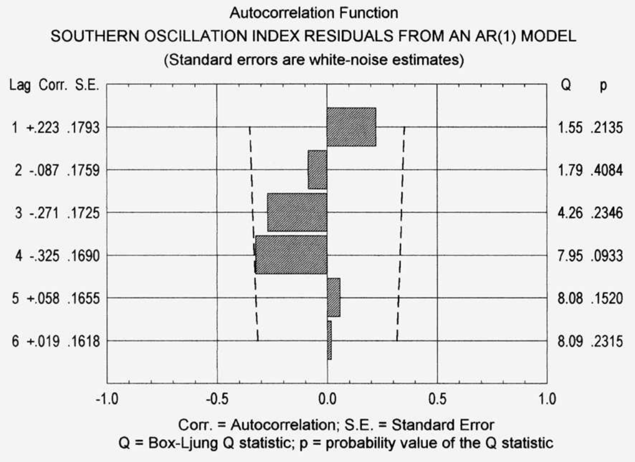

Figure 6: Correlogram of the residuals of standardized Southern Oscillation Index from AR(1) model.

The relationship between SLEWL and SSOI at lag one (i.e., six months) is not unexpected because when an El Niño or La Niña develops it takes some months for cyclonic storm tracks, rainfall, runoff, evaporation and temperature patterns to adjust. It is worthwhile to point out that Meadows et al. (1997) suggested that the response of lake levels to precipitation can take anywhere from three months to two years. These authors found that lake levels are correlated to precipitation levels of the preceding year. These antecedent precipitation levels may have been influenced by changes in cyclonic storm tracks across North America that have responded to the influence of El Niño or La Niña events.

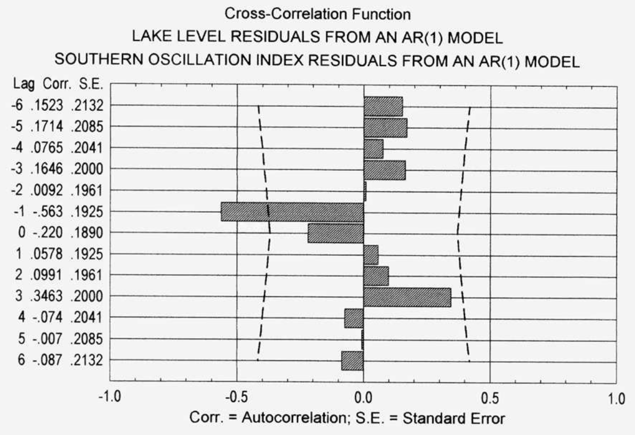

Figure 7: Cross-correlation of residuals from AR(1) model of Lake Erie water level fluctuations with residuals from AR(1) model of standardized Southern Oscillation Index.

Conclusions

The Lake Erie water level time series examined in this study is highly autocorrelated, and the Southern Oscillation Index time series is also significantly autocorrelated; standard regression methods used to estimate secular trends are, therefore, probably inappropriate. Because a properly fit time series model must have non-autocorrelated error terms (residuals), a statistical requirement for all regression and autoregressive models, Box-Jenkins (or modern) time series analysis is more suitable for tracking the serial behaviour of these two variables than standard regression models. The Box-Jenkins modelling procedures have provided appropriate results which indicate that a first-order autoregressive model provides the best fit for the SLEWL and SSOI data sets. It is apparent that the serial behaviour of short term fluctuations in Lake Erie water levels and the Southern Oscillation Index behave in a stochastic manner. Although this research has demonstrated that Lake Erie water levels fluctuate in response to El Niño/Southern Oscillation events, we need to determine the time lags between specific and recurring El Niño or La Niña events and changes in water levels. A more elaborate study is currently investigating the controls on the lag effects, and the processes which are linked to ENSO. In addition, a longer time series (1918 to present) of SOI and LEWL data are being analyzed to determine whether there are also distinct relationships over the long term between ENSO events and Lake Erie water levels.

Since many problems associated with shoreline management are related to rising or falling water levels, more reliable estimates of the temporal behaviour of water levels are needed. A knowledge of the history of lake level fluctuations coupled with Southern Oscillation Index observations can provide a relevant means of making short term predictions about water level behaviour that could affect short term shoreline planning decisions. The results obtained from this research will be helpful for the construction of models to simulate water level scenarios relative to shoreline management. The models can then be useful for dealing with associated water level problems. Ongoing research provide evidence that shows that high lake levels during El Niño events, and fairly low water levels during La Niña events, create problems for shoreline residents. For instance, during the 1995 La Niña event, shoreline dwellers along Lake Erie, Ontario, complained that they could not gain access to the Lake from their boat slips. Also during this La Niña event, farmers along Lake Erie, Ontario, suffered a drought.

Further study of the relationship between water levels and the El Niño-La Niña/Southern Oscillation phenomena may lead to a more effective means of coping with the dynamics of water level change in the Great Lakes.

References

Andrade, E.R., and Sellers, W.D. 1988. ‘El Niño and its effect on precipitation in Arizona and western New Mexico,’ *Journal of Climate*, 8: 403-410.

Bell, G.D., and Janowiak, J.E. 1995. ‘Atmospheric circulation associated with the Midwest floods of 1993’, *Bulletin of the American Meteorological Society*, 76(5): 681-695.

Bradley, R.S., and Jones, P.D. (eds.) 1992. *Climate since A.D. 1500*. London and New York: Routledge.

Cayan, D.R., and Webb, R.H. 1992. ‘El Niño/Southern Oscillation and streamflow in the western United States’. In *El Niño. Historical and paleoclimatic aspects of the Southern Oscillation*, eds. H.F. Diaz and V. Markgraf, pp. 29-68. Cambridge, UK: Cambridge University Press.

Chatfield, C. 1985. *The analysis of time series: An introduction*. London and New York: Chapman and Hall.

Diaz, H.F., and Kiladis, G.N. 1992. ‘Atmospheric teleconnections associated with the extreme phase of the Southern Oscillation’. In *El Niño. Historical and paleoclimatic aspects of the Southern Oscillation*, eds. H.F. Diaz and V. Markgraf, pp. 7-28. Cambridge, UK: Cambridge University Press.

Environment Canada 1997. Great Lakes monthly mean water level data. Ottawa, ON: Canadian Hydrographic Service, Environment Canada.

Glantz, M.H. 1996. *Currents of change: El Niño's impact on climate and society*. Cambridge, UK: Cambridge University Press.

Hastenrath, S., and Greischar, L. 1993. ‘Circulation mechanisms related to northeast Brazil rainfall anomalies,’ *Journal of Geophysical Research*, 98: 5093-5102.

Kane, R.P. 1997. ‘Relationship of El Niño-Southern Oscillation and Pacific Sea Surface Temperature with Rainfall in Various Regions of the Globe,’ *Monthly Weather Review*, 125: 1792-1800.

Kiladis, G.N., and Diaz, H.F. 1989. ‘Global climate anomalies associated with extremes in the Southern Oscillation’, *Journal of Climate*, 2: 1069-1090.

Meadows, G.A., Meadows, L.A., Wood, W.L., Hubertz, J.M., and Perlin, M. 1997. ‘The relationship between Great Lakes water levels, wave energies and shoreline damage’, *Bulletin of the American Meteorological Society*, 78 (4): 675-683.

Nicholls, N. 1993. ‘ENSO, drought and flooding rain in South-East Asia’. In *South-East Asia's environmental future: The search for sustainability*, eds. H. Brookfield and Y. Byron, pp. 154-175. Tokyo, Japan: United Nations University Press and Oxford University Press.

Philander, S.G. 1990. *El Niño, La Niña, and the Southern Oscillation*. San Diego, CA: Academic Press, Inc.

Quinn, F. 1978. 'Hydrologic response model of the North American Great Lakes', *Journal of Hydrology*, 37: 295-307.

Quinn, F., and Guerra, B. 1986. 'Current perspectives on the Lake Erie water balance', *Journal of Great Lakes Research*, 12: 109-116.

Quinn, F., and Neal, V.T. 1992. 'The historical record of El Niño Events'. In *Climate since A.D. 1500*, eds. R.S. Bradley and P.D. Jones, pp. 623-648. London and New York: Routledge.

Redmond, K., and Koch, R. 1991. 'ENSO vs. surface climate variability in the western United States', *Water Resources Research*, 27: 2381-2399.

Richards, K.S. 1979. *Stochastic Processes in One-Dimensional Series: An Introduction*. East Anglia: Concepts and Techniques in Modern Geography #23.

Ropelewski, C.F., and Halpert, M.S. 1986. 'North American precipitation and temperature patterns associated with the El Niño/Southern Oscillation (ENSO)', *Monthly Weather Review*, 114: 2352-2362.

Ropelewski, C.F., and Halpert, M.S. 1989. 'Precipitation patterns associated with the high index phase of the Southern Oscillation', *Journal of Climate*, 2: 268-289.

Shabbar, A., Bonsal, B., and Khandekar, M. 1997. 'Canadian precipitation patterns associated with the Southern Oscillation', *Journal of Climate*, 10 (December): 3016-3027.

StatSoft, Inc. 1997. *STATISTICA for Windows* [Computer program manual], Tulsa, OK: StatSoft, Inc.

Stone, R.C., Hammer, G.L., and Marcussen, T. 1996. 'Prediction of global rainfall probabilities using phases of the Southern Oscillation Index', *Nature*, 384: 252-255.

Suplee, C. 1999. 'El Niño/La Niña', *National Geographic*, 195 (3): 72-95.

Trenberth, K.E., and Hoar, T.J. 1996. 'The 1990-1995 El Niño-Southern Oscillation event', *Geophysical Research Letters*, 23 (1): 57-60.

Troup, A.J. 1965. 'The Southern Oscillation', *Quarterly Journal of the Royal Meteorological Society*, 91: 490-506.