# Wind-induced Microseisms from Large Lakes

**Bryan R. Kerman**

Atmospheric Environment Service
Canada Centre for Inland Waters
Burlington, Ontario, Canada

**Robert F. Mereu**

Department of Geophysics
University of Western Ontario
London, Ontario, Canada

**Denis Roy**

Faculty of Science
Queens University
Kingston Ontario

## Abstract

The characteristics of microseisms measured by seismometers near the shore of Lake Ontario and Great Slave Lake are analyzed. For Lake Ontario the rms levels in the 1 to 3 Hz band are coherent between stations widely separated around its western basin indicating a common generative mechanism. A distinct onshore intermittent flux of Rayleigh-like wave energy was detected at the onshore sites for both lakes. Microseismic energy in this band is correlated with the wind speed. The correlation improves as the winds are averaged into the past until an optimum is reached corresponding to the time constant of water wave generation by changing wind speed. For a given fixed wind speed, the microseismic energy correlates with the average fetch of the wind over the lake. The sensitivity to fetch effects is similar for both onshore and offshore stations indicating that shoaling is probably not a source. Niagara Falls which also can have a wind-dependent flow from Lake Erie causes measurable effect to at least 25 km but does not noticeably affect stations at a distance of 150 km.

It is suggested that the microseismic flux provides a natural, relatively inexpensive way to monitor the water wave field on such large lakes. Further, such seismic observations may provide useful insights into wave generation mechanisms, in particular a lake's response to variable wind speed, the onset of rough flow and the spatial variability of the wave field. Additionally a large lake may well prove to have a stronger source strength of microseisms than an ocean.

## 1. Introduction

Microseismic activity arising from oceanic storms has been known for a long time (Wiechert, 1904). Longuet-Higgins (1950) suggested that the seismic effect was due to the non-linear interaction of oppositely propagating swell and wind waves. A key prediction of that theory is that the seismic spectrum will be similar in form to that of water waves but at twice the frequency of the water waves and has been tested widely (e.g., Kibblewhite and Evans, 1986; Jacobs et al., 1993). A long standing alternative explanation (see Haubrich and McCamy, 1969 for a review) was that shoaling waves on a shoreline produced the seismic effect. Current research, as reviewed by Orcutt et al. (1993), in the previous meeting in this series, seeks to better understand the generation, propagation and bottom coupling of ocean-generated microseisms.

On the other hand hardly any attention has been given to the possibility that lakes are also microseismic sources. In a study some 40 years ago Lynch (1952, 1956) reported that he could detect microseismic wave energy at 0.5 Hz with the passage of storms over the Great Lakes. In another study relevant to this paper, Weichert and Henger (1976) noted the existence and basic characteristics of microseismic noise at Yellowknife, North West Territories. Their measured noise levels were distinctly higher in the summer than the winter when the lake was frozen over. They were also able to determine that the waves at about 1 Hz were travelling at about 3 km/sec from the direction away from nearby Great Slave Lake. Such a speed was considerably less than a P-wave (phase speed about 6 km/sec). Accordingly Weichert and Henger argued that the energy was propagating as a guided Rayleigh wave in an upper 1 km thick crustal layer.

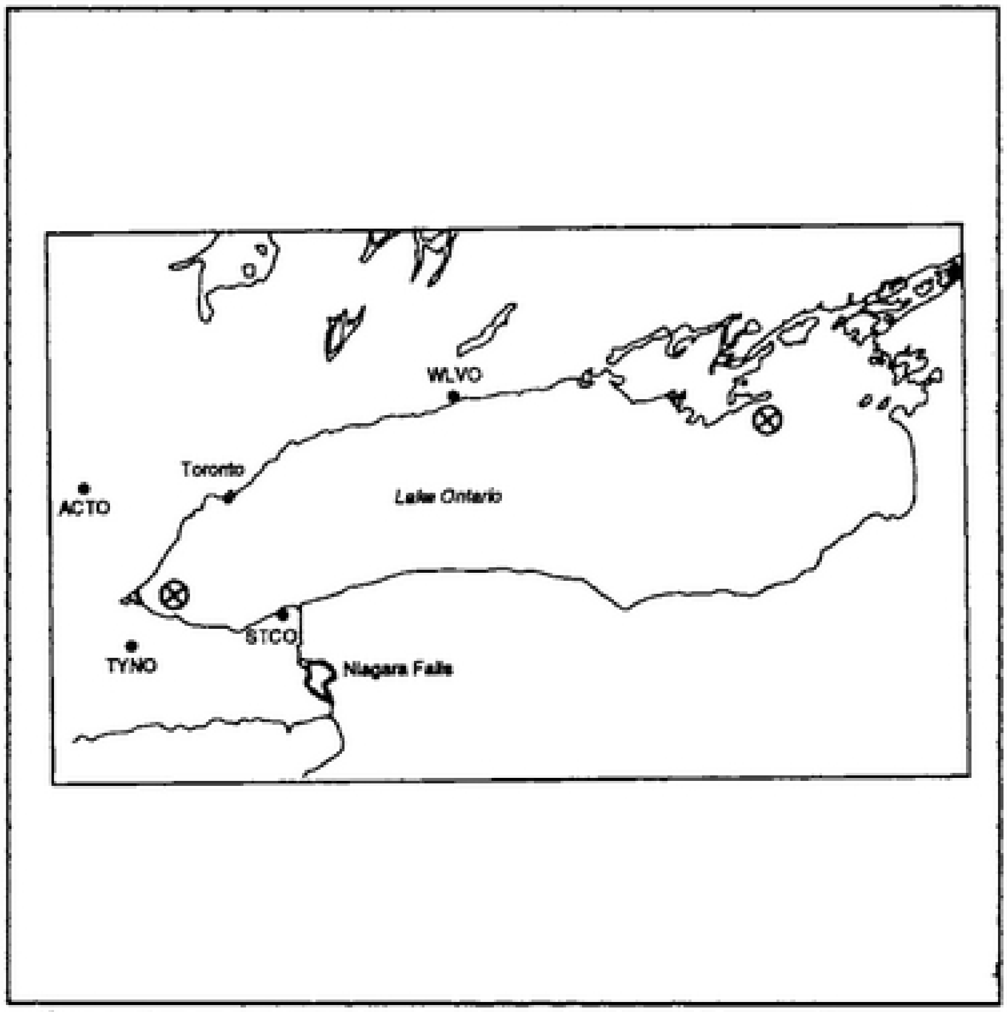

**FIGURE 1: Lake Ontario, showing seismic and buoy sites.**

Accordingly there is evidence of measurable microseismic energy radiating from large lakes such as Ontario and Great Slave. It is however an open question as to whether there is any evidence of the wave-wave mechanism as opposed to shoaling. It is also useful to attempt to quantify what is the level of microseismic energy close to the lake, what is its wind dependence, and what wave properties does the seismic activity have?

## 2. Lake Ontario

The microseism data from the Lake Ontario region has been discussed by Kerman and Mereu (1993). We will direct most of our attention here to observations taken at Wesleyville (WLVO), with some discussion of the other sites - St Catharines (STCO), Tyneside (TYNO) and Acton (ACTO) (Fig. 1). Vertical component data was collected at all sites from Oct 2 to Dec 2. Three component data was also collected from Nov 25 to Dec 2, 1992. Data were collected for 10 minutes at about 4 am local time to avoid cultural noise. All data were low-pass filtered below 3 Hz. The seismometers have a natural roll-off below 1 Hz thus limiting the frequency band to 1-3 Hz. Over-lake winds for the experiment were measured on 2 weather buoys operated by the Atmospheric Environment Service.

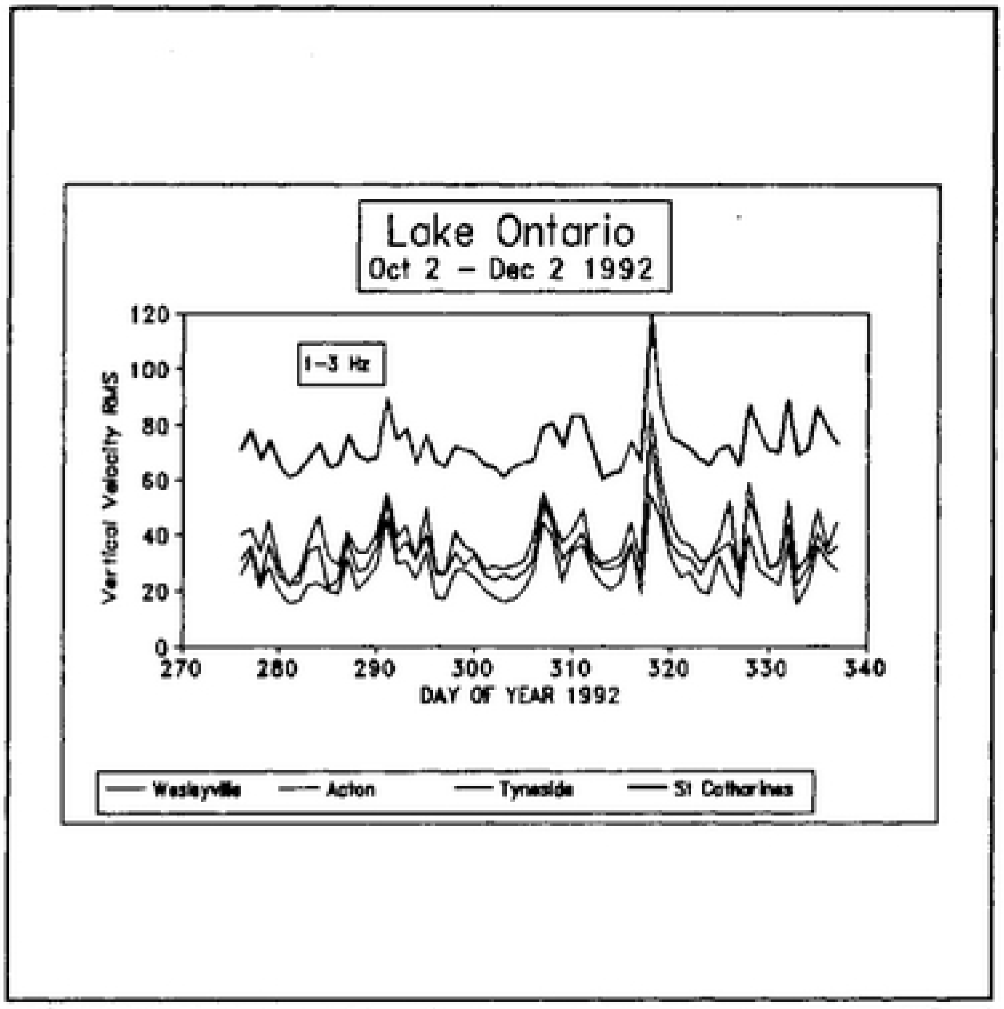

FIGURE 2: Variation of low frequency microseismic energy at the 4 seismic sites.

## 2.1 RMS Characteristics

The daily record of the 1-3 Hz vertical component rms from the 4 stations is shown in Fig 2. The signal between the stations is highly coherent, with a typical $R^2$ correlation of 0.85 between pairs of stations. WLVO has the lowest consistent response (minimum about 15 nm/sec) while STCO has a consistently high response (minimum 60 nm/sec). While part of the difference arises from various industrial activity and road traffic, as discussed below the proximity to Niagara Falls also affects the signal at SCTO.

The inter-station coherence implies that the source of microseisms must be common to all the stations. Such a common source might be distant (teleseismic) or local. It is conceivable that the source arises from the straining of tree roots, in a regionally coherent wind field. The strong coherence allows us to reduce the analysis to that of a single station, and we have chosen WLVO because of its low background noise.

The 3 component rms records for WLVO (not shown) indicate that the vertical component exceeds the horizontal components by a factor of about 1.5. The theoretical ratio of vertical to horizontal amplitude for Rayleigh waves for a homogeneous half-space is about 1.4 (Gutenberg, 1958). The agreement may be fortuitous as seen later as the space is not homogeneous and there is considerable non-Rayleigh energy included in the rms estimates.

## 2.2 Spectral Properties

For Rayleigh waves, the horizontal velocity component leads the vertical component by $90^0$ in the direction of propagation. Accordingly a test of the hypothesis of the existence of a Rayleigh wave source is that there be significant quadrature energy in a cross-spectral analysis between the vertical and horizontal components (Darbyshire, 1954). The polarization properties of such a wave also allow for a determination of the direction of its propagation. Fig. 3 presents the spectral properties (vertical velocity spectrum, north-south quadrature and coherence). The quadrature indicates a flux of Rayleigh-wave energy from the direction of the lake in the frequency band from 0.6 and 2.5 Hz. The vertical velocity spectrum has a maximum near 1 Hz and decreases consistently above 1.2 Hz. This maximum may be an artifact of the instrumental filtering of the seismometers below 1 Hz.

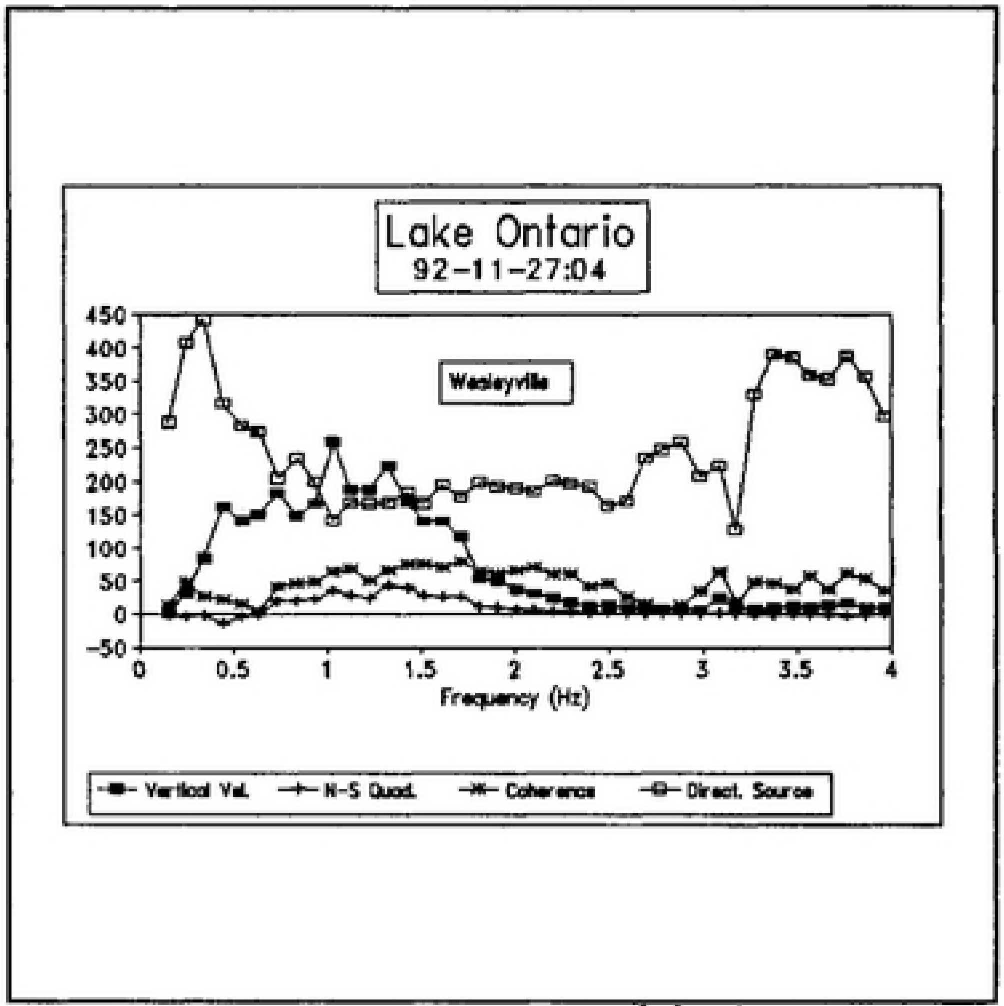

**FIGURE 3: Auto- and quadspectra (nm$^2$s$^{-2}$Hz$^{-1}$) and coherence (x100) for the vertical and north-south components.**

The quadrature (Fig. 4) at different frequencies shows evidence of a broad maximum in the amplitude for waves with an on-shore direction (180-230$^0$). There is no indication of a major source originating along the shoreline (260$^0$ and 80$^0$). The process is maximized for waves of about 1-1.5 Hz frequency with no evidence of a preferred direction below 0.5 Hz. The auto-spectra for WLVO (Fig. 5) have a common shape and decrease rapidly with a slope of approximately -5 at frequencies above 1 Hz. This slope conforms to the well-documented spectra of water waves.

While such results tend to confirm wave-wave interactions in the body of the lake as the source, there are other less comforting results. Quadrature spectra for the other sites did not provide evidence of a Rayleigh wave energy flux away from the lake. The reason is believed to be the additional distance from the lake and the effect of the Niagara escarpment in scattering the wave energy (Asten, 1978) for the sites ACTO and TYNO. Further STCO was dominated by a highly energetic and directional Rayleigh-like flux originating from Niagara Falls. Also the apparent water wave spectral form may be fortuitous and related to crustal attenuation properties. In their studies of oceanic microseisms, Kibblewhite and Evans (1986) concluded attenuation is not a problem over much larger distances than the size of Lake Ontario. With this caveat on attenuation, we conclude that the wave spectra offer support for retaining the wave-wave interaction process as a strong candidate for the source of the microseisms, carried as Rayleigh interfacial waves.

### 2.3 Wind Effect

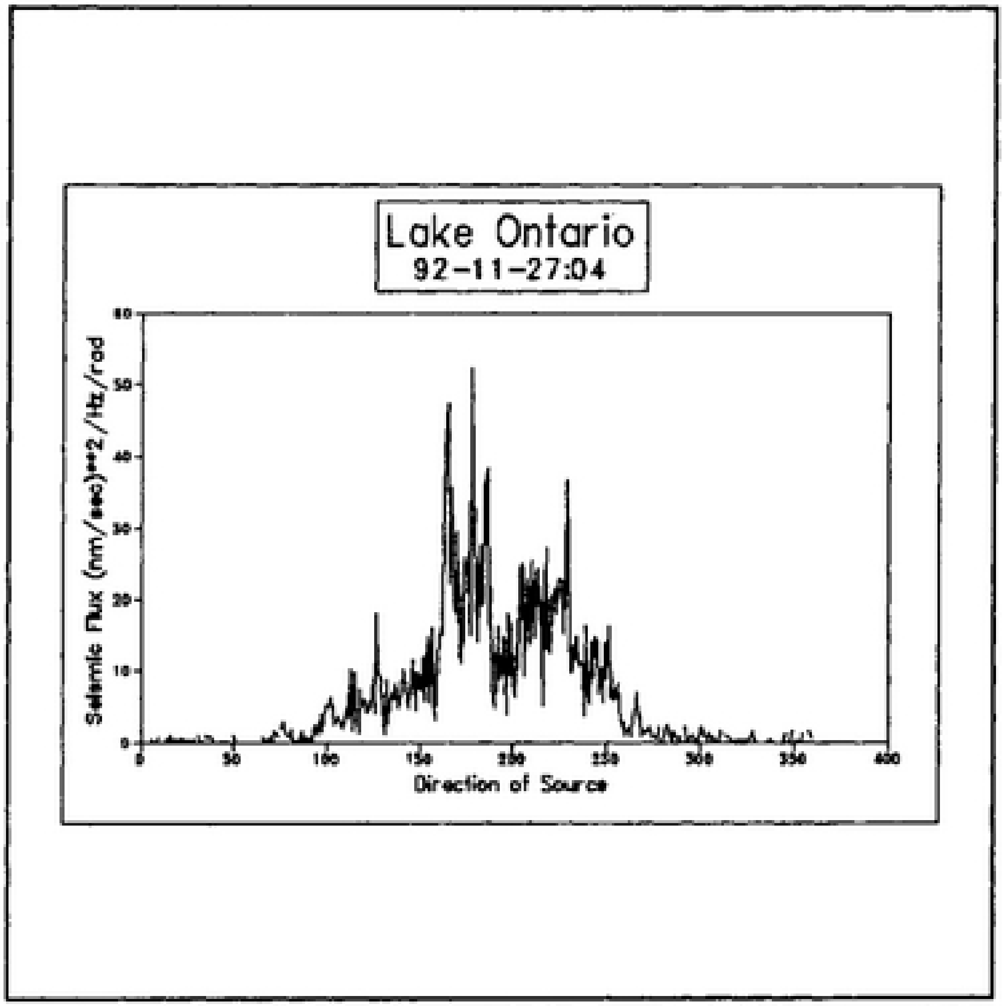

**FIGURE 4: Rayleigh wave flux at 1.59 Hz at WLVO in terms of the direction to its source.**

The hypothesis that more microseismic energy will be produced by more intense wave-wave interaction, itself associated with larger amplitude water waves produced by stronger winds is tested in Fig. 6. The trend of the data demonstrates conclusively that wind is a major controlling variable. Accordingly teleseismic activity can be eliminated as a major source of the variance. Wind as a controlling variable does not agree with the recent result presented by Webb (1992) for oceanic microseisms. There a saturation effect is found, similar to the well-known saturation of wind wave spectra. Clearly the lake results show no indication of saturation. However in the ocean an ocean bottom seismometer may be receiving wave energy from multiple storm centres simultaneously. Another test (not shown) reveals, for a given wind speed, more microseismic energy is received if the wind blows along the long axis of the lake, presumably associated with enhanced wave-wave interaction. This anisotropy rules out tree root effects which would be isotropic with respect to wind direction. Also if shoreline shoaling of wind-driven waves is the cause of the wind-correlated microseisms one would expect a stronger signal on the downwind side with onshore breaking compared to the upwind side where wave growth is only beginning. However no measurable difference between upwind and downwind stations for a given wind speed was found, thereby further diluting the case for shoaling.

By the process of elimination, the source of the microseisms must be the lake surface itself. However any further elaboration of the details of the mechanism requires experimentation similar to other ongoing research such as the SAMSON experiment (Babcock et al., 1993).

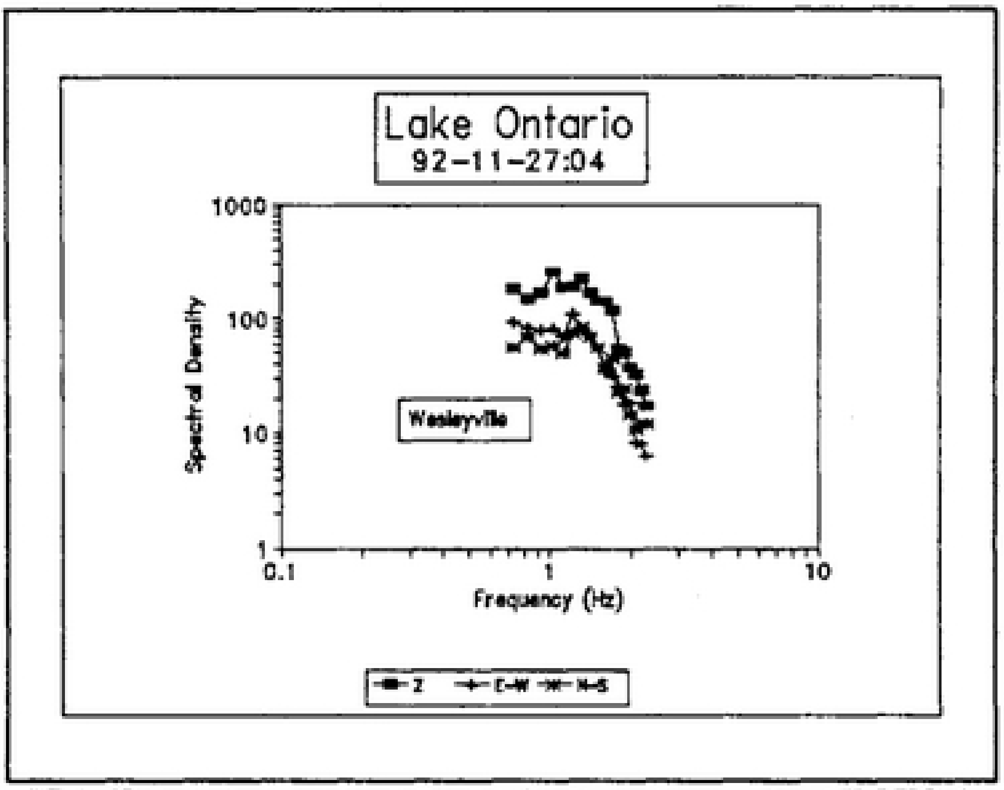

FIGURE 5: Autospectra of the 3 velocity components at WLVO for frequencies with an onshore Rayleigh flux. ($nm^2s^{-2}Hz^{-1}$)

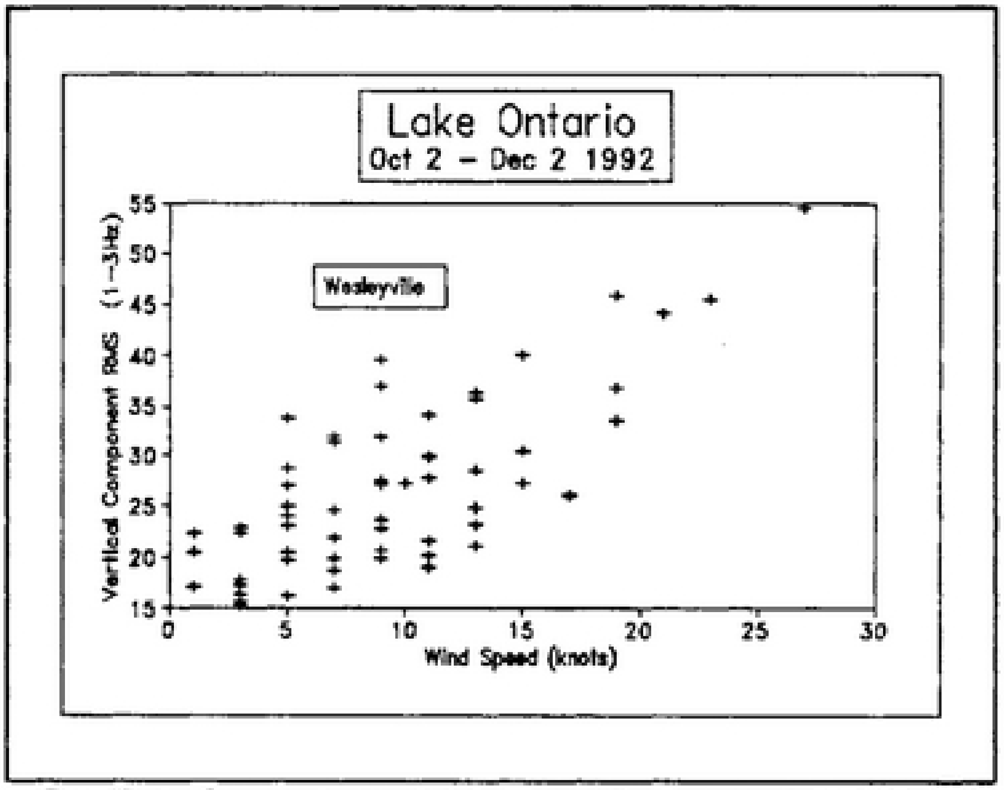

FIGURE 6: Comparison of 1-3 Hz vertical rms at WLVO with averaged buoy winds.

## 2.4 Niagara Falls

The observation that St Catharines was strongly affected by Niagara Falls raises 2 questions - does it contaminate other stations and why is its response so coherent to the other stations, particularly the wind-dependency? It is shown in Kerman and Mereu (1993) that for west and south-west winds blowing along Lake Erie, pushing up a hydraulic head of water at the mouth of the Niagara River, an increased flow occurs down the river and over the Falls. Fig 7 shows the correlation of the total flow (over the Falls and through the hydroelectric generation plants) and the seismic response at St Catharines for west and southwest winds (as measured on Lake Ontario). This correlation disappears when the wind direction is such as not to push water into the river. However the correlation is retained with these non-west/southwest winds at the other sites.

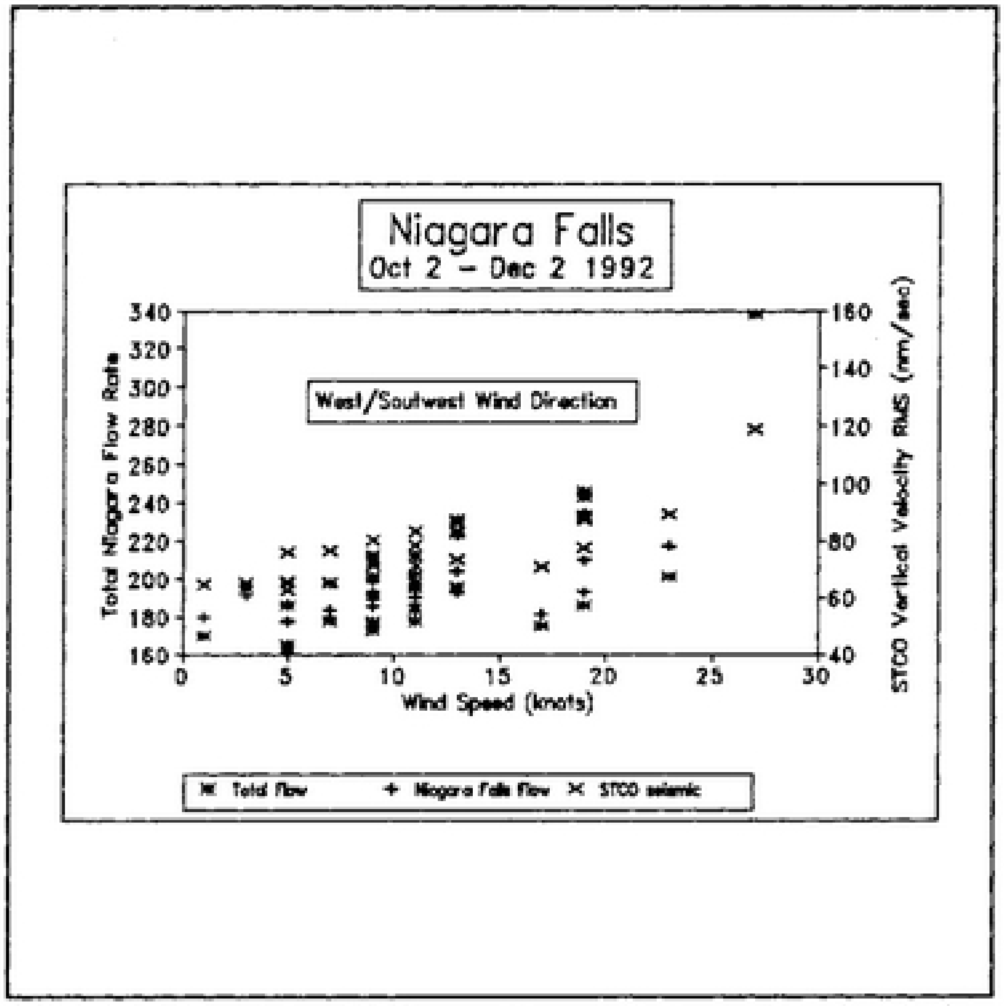

FIGURE 7: Flow (cfs x 1000) over Niagara Falls, combined with flow through hydroelectric generators, and seismic response at STCO when winds are from the west.

## 3. Great Slave Lake

The Yellowknife seismological array which has been in existence since the 1960's is situated about 15 km outside the city of Yellowknife, North West Territories, Canada. The centre of its 4 orthogonally located broad-band (0.003 to 7 Hz) stations is about 20 km from Great Slave Lake, a large lake about 50% larger than Lake Ontario covering about 29 $10^3$ $km^2$ with an average depth of about 100m. The eastern part, comprising about 40% of the total area, has limited fetch (and hence a reduced potential as a microseismic source) because of the existence of many islands.

The array has been developed to its present sophistication to detect nuclear testing in order to monitor compliance with various international treaties banning underground detonations. A problem of long standing (Weichert and Hengler, 1976) is the effect that the lake has on operations during the open water summer season. The additional noise level ascribed to the lake elevates the false alarm criterion. It was shown that whereas about 30 detections at the 50% false alarm rate occurred in winter the number rose to about 750 in summer, necessitating a special study and characterization of the open water season. In particular Weichert and Henger found that waves with a dominant frequency near 1 Hz occasionally could be tracked across the array from south to north at a speed of about 3 km/sec, primarily from direction $150^0$ which is down the long north arm of the lake. Such a wave speed is too slow for a compressional P-wave and was postulated to be a guided Rayleigh wave propagating in an upper 1 km thick layer of granite.

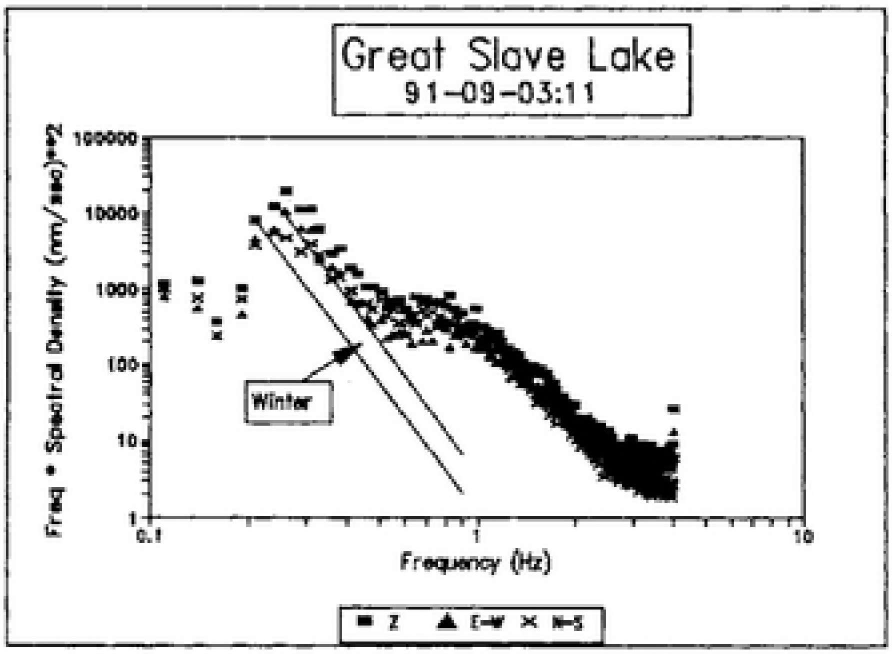

**FIGURE 8: Spectra of 3 velocity components, averaged over all broad-band sites for typical summer case. Note also limits of fitted winter spectra.**

The most obvious evidence of the role played by some water wave phenomenon was the significantly higher spectral levels above about 0.4 Hz in summer compared to winter, as discussed below. The seismic waves were found to attenuate rapidly inland away from the shoreline. Weichert and Henger argued that the gradual modulation of a wave train was not compatible with an impulsive source associated with shoaling. They found reasonable agreement with a prediction (Barr, 1971; Clee et al., 1974) that the frequency of the most energetic microseismic wave was related to the depth of the granite layer, $h$, and the shear velocity, $\beta$, by $f=\beta/4h$. This raises the possibility of a resonance between the underlying layer and the frequency of excitation.

## 3.1 Experiment

About 60 cases, of 10 minute duration on the hour, of broad-band, 3 component velocity at up to 4 stations were extracted from the data archives of the Seismology Division of the Geological Survey of Canada. The cases were originally selected to a) provide a uniform distribution of wind speeds as sampled at the nearby Yellowknife airport and b) to occur at a time of the year to assure the lake was either free of ice or frozen over. The data were Fourier analyzed, limited in display to 0.1 to 4 Hz, and averaged over the number of stations reporting at the observation time (typically 3 or 4). Fig 8 displays both the typical spectra of the 3 components during open water conditions as well as the bounds of the best fit lines during the winter. Clearly, as reported by Weichert and Henger, the seismic energy is enhanced during open water conditions particularly in the 0.7 to 1 Hz region. As discussed below it is not clear whether the enhanced energy extending to 0.25 Hz is all locally generated. The well-defined slope of the wintertime spectra is about -5, indicating that the low frequency source may also be associated with water waves.

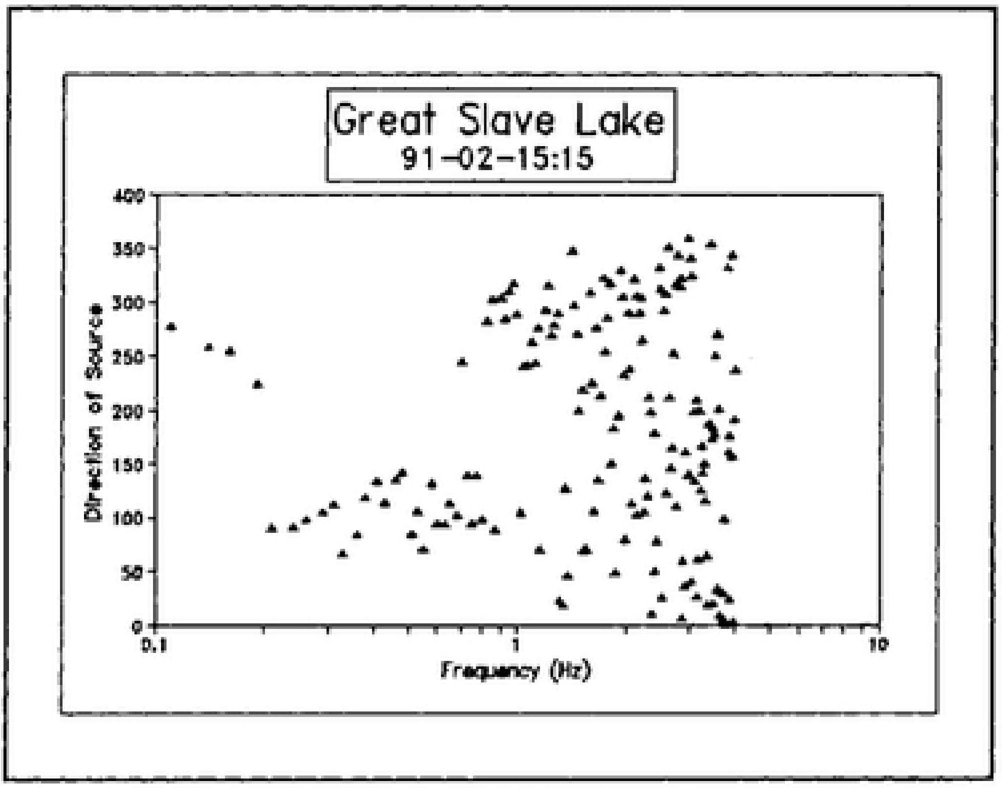

**FIGURE 9: Direction of Rayleigh wave flux propagation to Yellowknife array - wintertime, frozen lake conditions.**

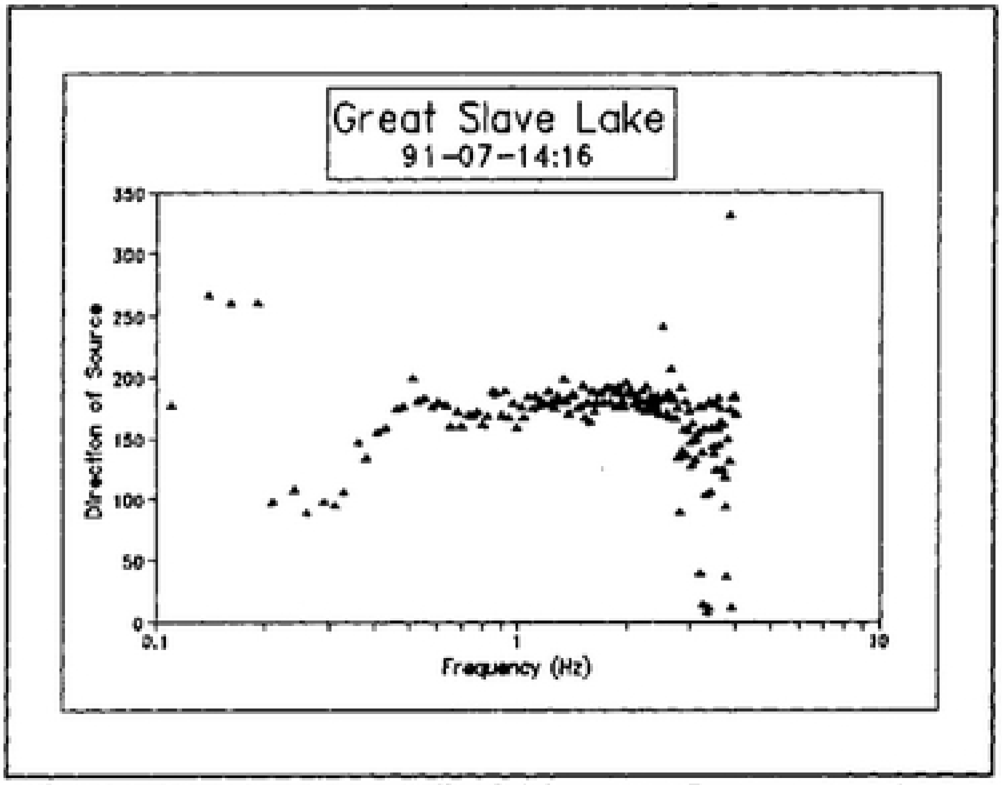

**FIGURE 10: Direction of Rayleigh wave flux propagation to Yellowknife array - summertime, open water conditions.**

## 3.2 Localization of Sources

The direction of sources was determined for the Great Slave Lake data in the same manner as for the Lake Ontario data - by assuming a Rayleigh wave flux, and using its polarization properties to determine its direction of propagation. The direction of sources for a typical wintertime case is given in Fig. 9. For the extremely low frequencies, below 0.2 Hz the source lies across the Rocky Mountains towards the Gulf of Alaska. In the range 0.2 to about 0.8 Hz, the source lies to the east across the Precambrian Shield towards Hudson Bay, and perhaps beyond to the North Atlantic Ocean. At higher frequencies the direction to the source is unclear, although there is a preponderance of individual estimates lying in a $\pm 60^0$ sector about north, possibly associated with Arctic ice effects.

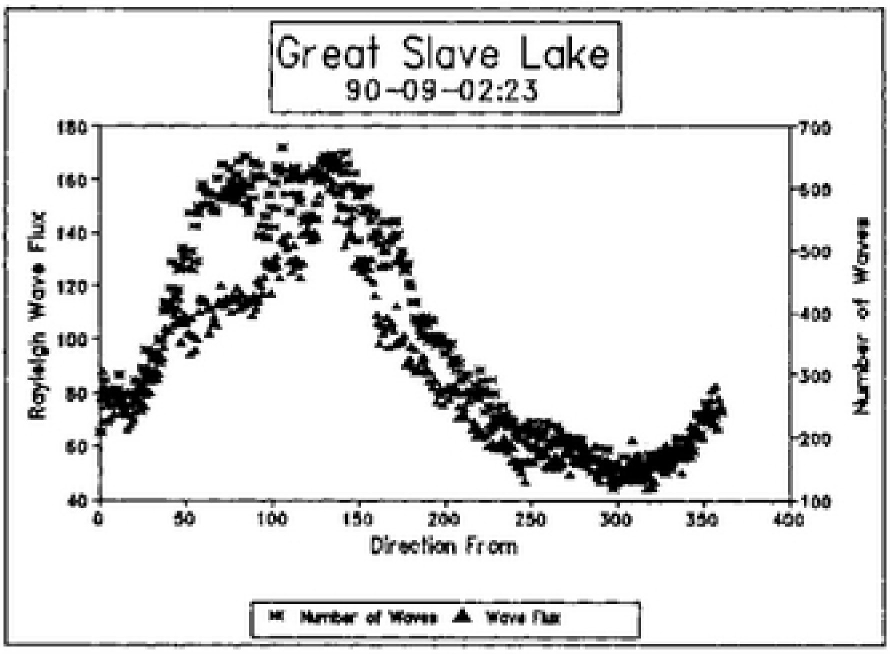

**FIGURE 11: Number and direction of Rayleigh waves measured at Yellowknife array in open water conditions.**

The situation changes dramatically for the open water cases as seen in Fig. 10. Whereas there is still evidence of a source to the west below 0.2 Hz and from the east between 0.2 and 0.4 Hz, otherwise the flux is entirely from the south, from the direction of Great Slave Lake. The southerly flux persists from 0.5 to at least 2.5 Hz until lost in noise originating from the direction of Yellowknife. On this basis it is probably unlikely that much of the enhanced, summer to winter, energy evident in Fig. 8 below 0.4 Hz can be associated with the lake. However the directions of flux are not strictly narrow as implied by Figs 9 and 10. Fig. 11 presents the number and total flux from a given direction for another open water case. There is a broad source in the number of waves extending from $60^0$ to $180^0$. The Rayleigh wave flux however peaks near $150^0$. A further breakdown with frequency (not shown) shows that much of the higher frequency flux is propagating from the south but the lower frequency flux extends in a broad maximum from east around to south. It is hypothesized that the extra flux from the south is due to scattering of the teleseismic Rayleigh flux, initially in the directional window between $60^0$ and $120^0$, towards a more northerly path. Whatever the cause the result is a confusion of exactly which seismic waves are associated with the Hudson Bay and the Great Slave Lake sources. An attempt to distinguish local and distant waves on their ratio of vertical to horizontal energy was inconclusive. Both wave sources are intermittent in a manner similar to those emanating from Lake Ontario (Kerman and Mereu, 1993). It remains to develop a discriminator between the two sources.

## 3.3 Response to Changing Wind

The open-water quadrature arising from the Fourier decomposition invariably indicated a southerly flux above 0.7 Hz as discussed above. To provide a consistent estimate of Rayleigh flux in the frequency range (0.4 to 0.6 Hz) a somewhat ad-hoc approach was applied to separate the wave sources. It was assumed that the distant lower frequency source evident near 0.2 Hz would decrease with frequency as in the wintertime case (Fig. 8) as $f^{-5}$. The excess energy above the projection was ascribed to the local lake effect. The resulting spectra associated with local effects above about 0.4 Hz also display a -5 slope. The quadrature were weighted by the ratio of the estimates of local to distant energy and compared with the wind speed from Yellowknife (not shown). The results were unsatisfying, indicating only weak evidence of a correlation with wind speed.

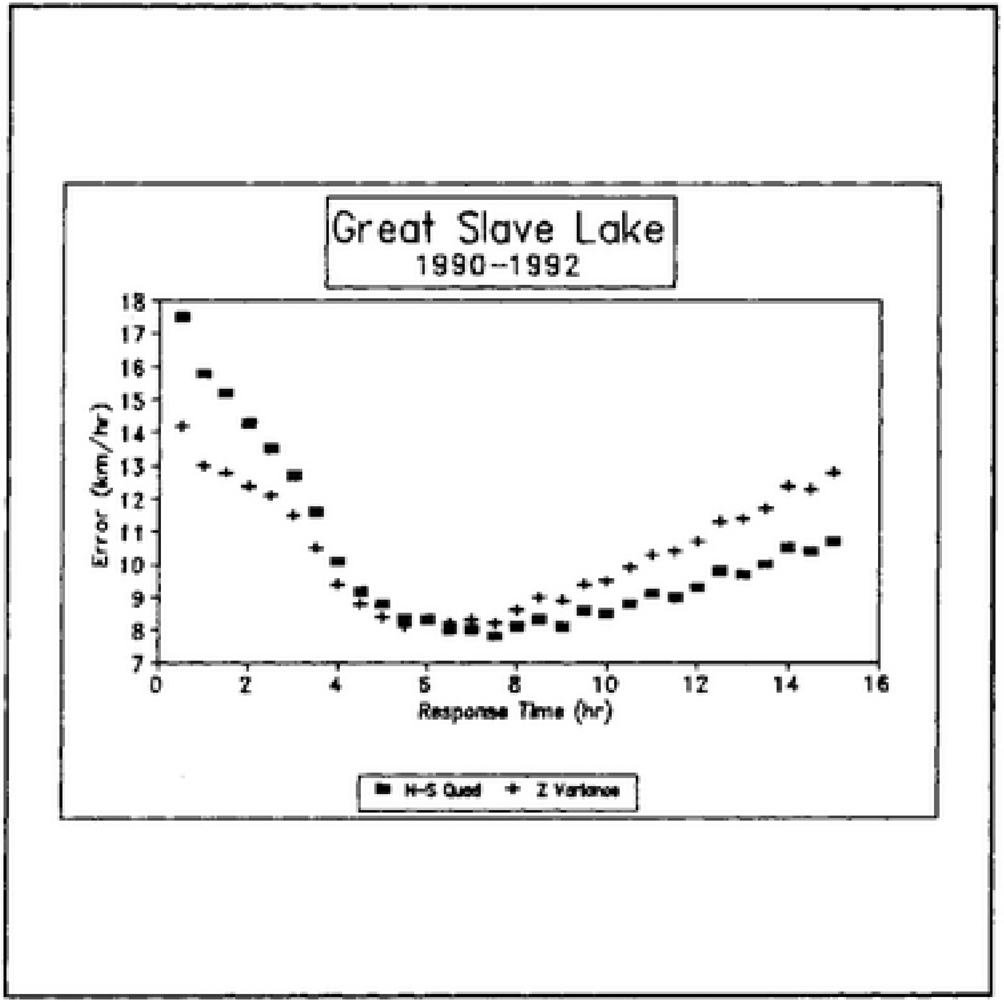

**FIGURE 12: Error in fit of seismic energy/flux to winds filtered using an exponential response into the past.**

The reason for the poor correlation was not immediately obvious. Eventually it was realized that the wind was only a surrogate for wave action, and that, as is well-known, the state of the wave field also is a function of the duration that a given wind speed has persisted. Unfortunately much of the original, specially selected higher wind speeds occurred in rapidly evolving weather such as fronts. To study the effect of wind duration, the winds were reanalysed using an exponential filter of the form, $\exp-(\delta t/\tau)$, where $\delta t$ is time into the past and $\tau$ is an arbitrarily selected time constant. The data set of quadrature and filtered winds, for each selection of the time constant, were fitted by linear regression. The error of the fit for each time constant is shown in Fig. 12. The error, expressed in terms of wind speed, is reduced from about 18 to 8 km/hr as the time constant is increased from no memory to one of effectively 6-7 hours. It is argued that the minimum error point corresponds to the response time for waves on the lake driven by variable winds. Ideally a wind-wave model (e.g., Clodman, 1989) could be used to test the response time hypothesis.

The resulting, minimum error, fit between the north-south quadrature and the filtered winds is given in Fig. 13. The rms quadrature rises from about 14 nm/sec at 15 km/hr to about 40 nm/sec at 35 km/hr, while the vertical component rms varies from about 22 to 84 nm/sec over the same wind speed range. Weichert and Henger report a value of 28 nm/sec for an October day based on their spectra. An interesting feature of Fig. 13 is the projection by the best fit line to insignificant microseismic energy below a wind speed of about 15 km/hr. Such a threshold seems too low to be associated with visible breaking waves, usually thought to appear above about 30 km/hour. However it might be associated with the transition from smooth to rough wall flow at the air-water interface when significant momentum begins to be transferred from the air to the water waves, and consequently wave growth. In any account the seismic wave measurements are capable of providing an integrated view of the lake's wave field, and its response to an imposed wind field.

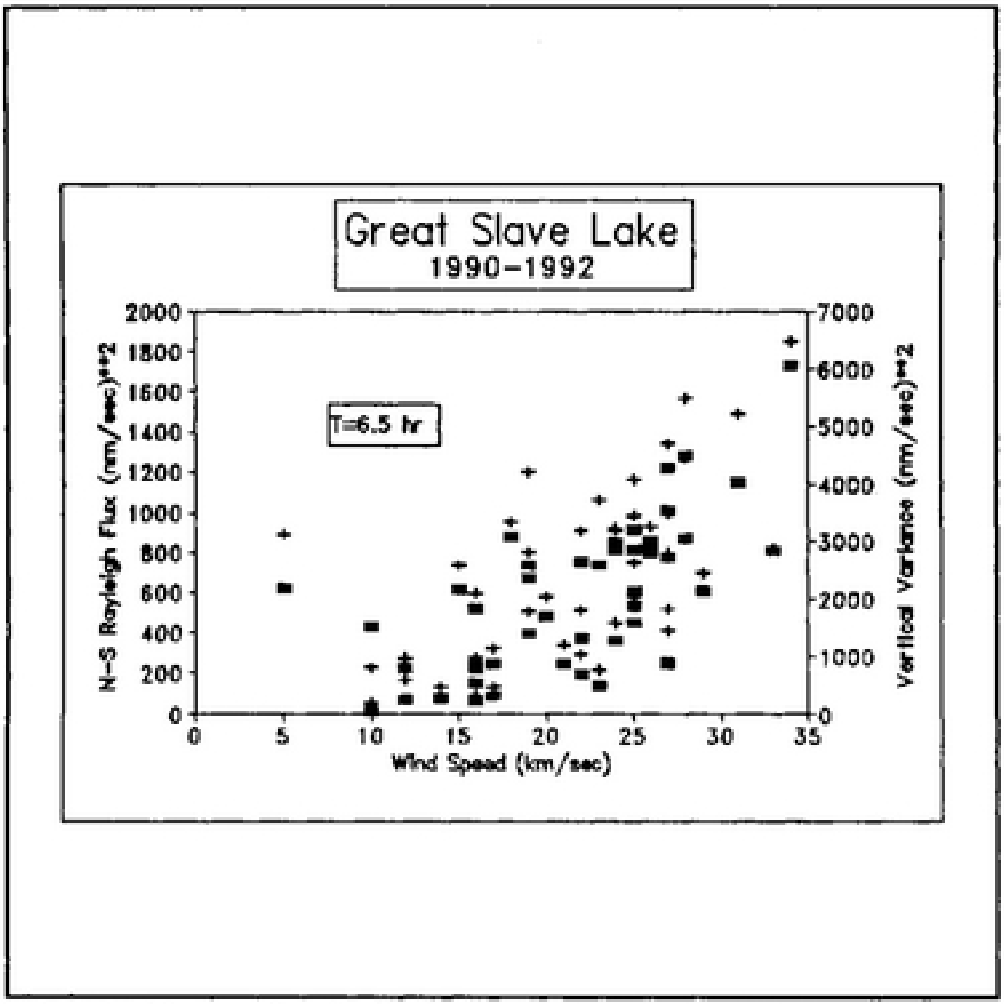

**FIGURE 13: Best fit of seismic energy and Rayleigh flux with filtered winds.**

## 4. Concluding Discussion

Analysis of the low frequency seismic records near Lake Ontario and Great Slave Lake have clearly shown that a distinct, measurable, and intermittent flux of Rayleigh waves emanate from the large lakes. Seismic spectra mirror those of water waves. There is no evidence of shoreline generated energy reaching the seismometers, as close as 1 km from a shore. It is reasonable to discard competing explanations involving teleseismic, tree root noise and shoreline shoaling in the range of 0.4 to 2 Hz. However flow at Niagara Falls does act as a local source of seismic activity, both as a steady background and a wind-dependent supplement, at least to a radius of 25 km which encompasses St Catharines.

A quadrature analysis, used to isolate Rayleigh-like waves from body and shear waves, as applied to the Great Slave Lake data have provided new insights into the time response of a lake to changing winds. It is suggested that seismic waves observed on the shore may be more than a curiosity - they might be a better measure of the lake-wide wave field than the instantaneous wind speed. Considering how much more buoy systems cost to install and maintain, the cost of data telemetry, their weather dependent errors, and localness, the use of a seismometer to monitor a lake's areally-averaged wave field is inexpensively attractive. Alternatively it is conceivable that an array of seismometers could be developed to select Rayleigh waves emanating from a given direction to give some idea of local variability of the water wave field. The intermittency of the process implies that either the source or the transmission through the earth is intermittent. It would be useful to determine which process, if not both, is responsible. If it is the source which is intermittent further analysis may provide more insight into the natural variability of wave generation.

From the original question posed by this research into whether a large lake could produce microseisms, it may be now be reasonable to expect that such lakes may be more efficient than oceans in such a process. What may divide them is simply the larger integrated effect over a larger area in the case of the ocean. The premise that the lake has a larger source strength is based on the work of Jacobs et al. (1993) who showed that the attenuation with depth into the water of pressure fluctuations in the microseismic band for lakes as shallow as Ontario or Great Slave Lake (average depth of the order of a 100 m) is sufficiently slow that the pressure effect on the bottom will be considerably larger. However wind wave development will be less on fetch-limited lakes.

While considerable evidence has been accumulated to support the Longuet-Higgins mechanism of wave-wave interaction (i.e., the period doubling observations of Jacobs et al., 1993) we suggest that the definitive experiment to unequivocally determine the source mechanism has yet to be performed. In the future we intend to compare water wave and broad-band noise from both a shoreline and bottom-mounted seismometer for single and double frequency effects. An estimate of wave-wave interaction intensity requires access to a wind-wave directional buoy. Such a study might be better conducted on a lake such as a Ontario or Great Slave Lake as the source is singular, contained and finite, in fact possibly stronger per generating area than the ocean.

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## Acknowledgements

The authors would like to thank B. Dunn and S. Winnardhi of the University of Western Ontario, Linda Mortsch and Ron Fordyce of the Atmospheric Environment Service, Len Falkiner of the Canada Centre for Inland Waters, and Bob North of the Geological Service of Canada for their help in acquiring various data used in this study. Support for the maintenance of the Southern Ontario Seismic Network is provided by an Ontario Hydro research contract.