Spatial patterns of zooplankton and water currents near the confluence of two major fetches in Lake Opeongo, Ontario

by

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Abstract:

This study combines Optical Plankton Counter data on zooplankton abundance and Acoustic Doppler Current Profiler data on water currents to test hypotheses about spatial zooplankton distributions near a major point of land affecting local wind and water current patterns. Data were collected by repeatedly sampling a 2 km linear transect in the South Arm of Lake Opeongo, Ontario, Canada during July, 2008. Moving Split Window techniques were used to identify breakpoints in both zooplankton biomass concentration and a measure of water turbulence, and confirmed an effect of the topographic feature on local zooplankton distributions. Using additional data collected in 2001 and 2003, zooplankton abundance distributions were also tested under three wind speed ranges predicted from physical principles to correspond to varying stability of the water column. Significant differences were found in the variability and patch sizes of the distributions, indicating the importance of wind speeds on zooplankton patchiness.
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Introduction:

Grazers play an integral role in any ecosystem, and the role of zooplankton in aquatic ecosystems is no exception. Zooplankton provide the trophic link between the carbon-fixing phytoplankton and the various species of fish that exist in lake ecosystems. Understanding what determines zooplankton community structure is critical in order to better comprehend and predict the functioning of aquatic food webs. Zooplankton distribution in lakes has been examined extensively in recent decades and has been shown to be heterogeneous over various spatial scales (Pinel-Alloul, 1995; Thackeray et al., 2004; Rinke et al., 2007). The mechanism underlying these spatial patterns has been proposed as the ‘multiple driving force hypothesis’ (Pinel-Alloul, 1995; Pinel-Alloul et al., 1999). This hypothesis proposes that both physical and biological forces are important and that large scale patterns are typically due to physical forces such as wind induced water currents, where as small scale patterns are created by both physical drivers (Langmuir circulation, upwelling or downwelling currents) and biological drivers (zooplankton swarming behaviour incited by photic changes, predator evasion or feeding on phytoplankton) (Pinel-Alloul, 1995; Thackeray et al., 2004). The small size of zooplankton restricts movement in the water column primarily to short migrations in order to find food or to avoid predation. Prior studies have identified that water currents, created by wind action, have the potential to overwhelm local movements and displace organisms over greater distances (Pinel-Alloul, 1995; Thackeray et al., 2004). These large-scale patterns, which act over scales on the order of kilometres, can explain some, but not all, of the variability found in zooplankton distributions. Small-scale forces are thought to be acting in concert with the large scale, wind-induced patterns, leading to this multiple driving forces hypothesis.
Until recently however, spatial patterns in zooplankton were difficult to observe, as data on zooplankton patterns has been difficult to obtain at small scales. Traditional plankton sampling techniques (plankton nets and traps, pump samples) lack the ability to continuously measure zooplankton concentrations across large bodies of water (Menza, 2003).

Recent work using automated zooplankton sampling techniques have successfully identified large scale zooplankton patterns in relation to prevailing wind conditions (Menza, 2003; Blukacz, 2007). Work conducted on Lake Opeongo, Ontario has shown evidence of higher plankton concentrations at the downwind side of the South Arm of the lake, which runs parallel to the longest wind fetch in the lake (Menza, 2003; Blukacz, 2007). This pattern of distribution is consistent with the idea of a ‘conveyor belt hypothesis’, where near-surface zooplankton are passively transported down-current and mass with warmer water near the surface at the downwind side of the lake (George and Edwards, 1976; Thackeray et al., 2004; Blukacz, 2009). This process, which acts at the large scale, was able to explain some of the variability in the zooplankton distribution (Blukacz, 2009). However, large scale (>1km) patterns only explained a portion of the variability in the data, and processes acting on smaller scales were hypothesized to have an effect on zooplankton distribution, but were previously difficult to characterize. This difficulty was in part due to the lack of real current data; Menza (2003) and Blukacz (2009) used wind as a proxy for water currents and estimated current speed and direction from wind speeds across South Arm. While this approach certainly provided useful information, it lacked the ability to resolve small scale current patterns that may have been acting along with biological processes to create plankton patchiness and variability at the fine scale.

In order to obtain current data needed to address small-scale patterns of zooplankton variability, hydroacoustic instruments have recently been used to measure water currents in conjunction with
zooplankton measurements in the Barents Sea (Edvardsen et al., 2003). This technique combining zooplankton and water current data proved informative in an oceanographic context, and it will be used in this study to provide the information needed to better understand small-scale patterns in a freshwater ecosystem.

Topography of the surrounding landscape can potentially be an important factor for small-scale variability in zooplankton distributions in a lake, as it can affect wind patterns that may create water currents on a small scale. The channelling effect of local topography on wind patterns was first identified in the South Arm of Lake Opeongo by Finlay et al. (2001). Blukacz (2007) identified a specific location in the South Arm of Lake Opeongo where zooplankton and water temperature spatial variability were elevated compared to the rest of the transect. This area was located in the middle of the South Arm near a peninsula named Windy Point, where the longest fetch of South Arm (winds predominantly from the west) joins with another long fetch coming from the south (winds predominantly from the southwest).

The effect of shoreline topography on water current patterns and associated zooplankton distributions has been described in both freshwater and oceanic contexts, (Wolanski and Hamner, 1988; Oyadomari and Auer, 2004) and peninsulas have been identified as locations where large-scale water current patterns can affect local zooplankton assemblages. In Lake Opeongo, a similar situation may be occurring at a smaller scale. A prominent peninsula may be creating small-scale water turbulence and zooplankton variability due to the convergence of wind-induced water currents. The formation of zooplankton aggregations as a result of the converging currents may have important ecological implications, as zooplankton predators, such as the Lake Cisco, could potentially gain increased foraging success if aggregations are occurring.
It has been shown that wind force directed across a fetch of a lake can be linked to the formation and preservation of near-surface water currents following the direction of the wind (Rinke et al., 2007; Loewen et al., 2007; P. Pernica and M. Wells, Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.). Blukacz et al. (2007) identified distinctive spatial patterns in zooplankton biomass, chlorophyll concentration and water temperature in Lake Opeongo under varying wind conditions that they termed low winds (< 3 m s\(^{-1}\)), moderate winds (3-7 m s\(^{-1}\)) and high winds (> 7 m s\(^{-1}\)). Without water current data, wind conditions were not directly linked to differences in the current regime present in the South Arm of the lake, making any causal relationships between wind and zooplankton patterns difficult to test.

The objectives of this study were to use continuous sensors to test the conjecture that previous observations of abrupt changes in the variance of zooplankton biomass (Blukacz, 2007) were associated with complex water movements near the confluence of two major fetches in the vicinity of a prominent point of land, and to establish direct relationships between water currents and zooplankton spatial patterns under varying wind conditions.

**Methods:**

**Study Site:** The sampling location for this study was Lake Opeongo, an oligotrophic lake, with four distinct basins, located in Ontario’s Algonquin Park, (45°42’N, 78°22’W). Lake Opeongo is dimictic, with a total surface area of 58.2 km\(^2\) and a mean depth of 14.8 m (Finlay et al., 2001). The focus of this study was the South Arm of Lake Opeongo, the largest of the lake’s four basins and the northern portion of which is a long, open body of water oriented in the direction of
prevailing westerly winds (Finlay et al., 2001). The sampling transect was one that runs parallel to the prevailing wind direction, with a midpoint off Windy Point and a total length of ≈2 kilometres (Fig. 1). This transect comprises roughly the middle portion of a longer one (approx 5 km) used by Menza (2003) and Blukacz (2009) and represents a trade-off between a longer transect that allows analysis at broader scales and a shorter one that allows multiple replicates and a larger sample size.  

Principal Data Sets:  

Two data sets were used for this study; the first data set was obtained during a sampling period on July 8th and July 9th 2008. A linear transect was repeatedly (n=10) sampled during daylight hours (10am – 6pm), to avoid any variation due to diurnal vertical migrations of zooplankton (Blukacz, 2009). Each transect combined Optical Plankton Counter data with Acoustic Doppler Current Profiler data, and were used to test of water turbulence and zooplankton distributions off Windy Point. A second data set included (n=12) linear transects sampled during daylight hours in July 2001, July 2003 and September of 2003 (A. Blukacz, Environment Canada, Toronto, ON, pers. comm.). These additional transects were originally 5-6 kilometres in length, spanning the entire South Arm, but for the purpose of this study were truncated to include only zooplankton measurements over the 2 kilometres centered on Windy Point. The second data set contained only Optical Plankton Counter data and was added to the first data set in order to test predictions about zooplankton distributions under varying wind conditions.  

Field Collections:  

Air temperature, wind speed and direction were recorded every 10 minutes by a weather station (model 05103, R. M. Young attached to a 10 × Campbell data logger) located on a small island
Fig. 1) Map of Lake Opeongo, Ontario, Canada indicating transect path, location of weather station and area of interest located off Windy Point. (Adapted from Blukacz, 2007)
in the South Arm, west of Windy Point (shown in Fig. 1). Spatial pattern in zooplankton biomass and horizontal water current velocity were measured with an Optical Plankton Counter (OPC) – (Model OPC-1 T, Focal Technology, Dartmouth, NS) and an Acoustic Doppler Current Profiler (ADCP) – (4 beam unit, Teledyne Workhorse, Teledyne RD Instruments, Poway, CA) respectively mounted on an aluminum boat, and simultaneously towed through the water at a constant depth and speed along the sampling transect.

The Optical Plankton Counter was mounted on a vertical aluminum pole attached to an aluminum beam mounted transversely across the boat. The OPC was set at a depth of 2.5 m which situates it in the epilimnion and below any surface bubbles that can cause false counts. During the sampling period in July of 2009, the thermocline was located at a depth of approximately 6-9 m (Fig. 2) (P. Pernica and M. Wells, Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.). The OPC was attached by cables to a deck unit which received both the OPC data and GPS (Trimble, Sunnyvale, CA) readings and was linked to an onboard computer for real-time data acquisition. The software used was OPC_DAS (Focal Technologies, Dartmouth, NS) which converted the raw OPC data into text files which were then analyzed using PV-WAVE Version 9.00 (Copyright 2007, Visual Numerics, Inc., Houston, TX).

The OPC measures zooplankton by projecting a highly collimated, 4 mm light beam across the tunnel opening through which zooplankton pass. Individual zooplankton block light in proportion to their body size as they pass through the tunnel. This blockage is recorded as a voltage change that has been calibrated to the diameter of a circle that would block the equivalent amount of light, defined as the equivalent circular diameter (ECD) by Herman (1992). While this method is appropriate for marine research, freshwater research requires certain
Fig. 2) Thermal profile for July 8\textsuperscript{th}, 2008 taken in the South Arm of Lake Opeongo. Thermocline begins at depth of approximately 6-7 metres, temperature microstratification of the epilimnion is indicated by dashed lines. Data provided by P. Pernica and M. Wells (Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.).
modifications to be made, due to the increased concentration and variety of zooplankton found in fresh water (Sprules et al., 1998). The OPC has the tendency to underestimate zooplankton numbers and overestimate zooplankton biomass due to coincident counts when multiple zooplankters pass through the beam simultaneously (Sprules et al., 1998). To correct for coincident counts, we followed the method devised by Sprules et al. (1998), reducing the sample tunnel width from 25 cm to 6.2 cm by introducing an acrylic insert (Fig. 3).

OPC equivalent circular diameter measurements (ECD) are converted into individual zooplankton mass using specific gravity of 1, and the volume of an oblate spheroid ($V$):

$$V = \frac{\pi}{6} * a b^2$$  

(1)

where $a$ is the major and $b$ is the minor axis. The major axis was equal to the ECD and the minor axis was the major axis divided by 1.8, which is the correction factor determined to be appropriate to correct for the Lake Opeongo zooplankton community that is dominated by copepods (Sprules et al., 1998).

The OPC produces a reading for every animal passing through the tunnel each half-second, and assigns each a size that can be converted to a mass using the methods outlined above. These observations were integrated into one-second intervals by summing the individual masses from adjacent half-second intervals and dividing by the volume of water passing through the opening during that second to determine biomass concentration ($\mu g \ L^{-1}$). The volume of water is calculated as the area of the tunnel opening (6.2 x 2.0 cm), multiplied by the distance traveled during the one-second interval. Boat positions were accurately measured by the GPS unit to a precision on the order of approximately 10 cm, and recorded every second and integrated into the
Fig. 3) Diagram of mechanism of Optical Plankton Counter, showing the opening width of 6.2 cm adjusted by the addition of an acrylic insert as per Sprules et al., (1998)
OPC files through the deck unit. The GPS coordinates were then converted to Universal Transverse Mercator units which were used to determine the distance travelled each second (typically 0.7 – 0.9 m). These calculations provided zooplankton biomass concentration (µg L⁻¹) roughly every 0.8 m along the 2 km length of the sampling transect.

The ADCP was mounted on an aluminum pole located on the opposite side of the boat from the OPC unit to prevent physical interference. The ADCP sampled horizontal water velocities and directions every 2-4 seconds, depending on the transect, at 10 cm depth bins from 1 m below surface down to 5 m (P. Pernica and M. Wells, Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.). Horizontal velocity measurements that fell into depth bins within 25 cm of the 2.5 m OPC depth were used. Due to the slight vertical movement of the OPC tunnel due to surface wave action, this range represented most accurately the current profile of the water at the OPC sampling tunnel.

Turbulent kinetic energy indicates the amount of mixing in the water column due to the force applied to the surface of the water by wind (P. Pernica and M. Wells, Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.). Low winds produce low turbulent kinetic energy, whereas high wind-forces on the surface of the water cause shearing which leads to higher turbulent kinetic energy. Horizontal turbulent kinetic energy (HTKE) is the measure of water turbulence chosen for this study.

\[
HTKE = \overline{u'^2} + \overline{v'^2}
\]

where \(u'\) and \(v'\) are the fluctuating components of the horizontal velocity, used to calculate HTKE for any depth bin.
\( \dot{u} = \bar{u} - \bar{U} \) and \( \dot{v} = \bar{v} - \bar{V} \), where \( \bar{u} \) and \( \bar{v} \) are the north-south and east-west instantaneous horizontal velocities and \( \bar{U} \) and \( \bar{V} \) are the north-south and east-west average horizontal velocities measured by the ADCP, calculated by a moving average over 50 seconds (P. Pernica and M. Wells, Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.). These calculations provided turbulence measurements for each of the 10 cm depth bins from the surface to a depth of 5 m, and HTKE values were found to be consistent over the entire range of sampling depths. For the purpose of this study, the turbulence measurements were averaged over the 50 cm depth range that corresponded to the OPC sampling tunnel opening. The HTKE measurements \( (m^2s^{-2}) \) were recorded at 2, 3, or 4 second intervals, depending on the sampling rate of the ADCP (P. Pernica and M. Wells, Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.). In order to ensure accurate comparisons of zooplankton concentrations and HTKE measurements, all transects were aligned to the same spatial resolution.

Due to technical difficulties with the OPC and ADCP instruments during the sampling period, only 10 transects were successfully sampled with synchronized zooplankton and water velocity measurements. During the 10 transects, the wind conditions remained relatively constant, with wind velocity measurements ranging between \( 3.3 \text{ m s}^{-1} \) and \( 5.2 \text{ m s}^{-1} \), all of which fell in the moderate wind group. The objectives of the study were divided into two sections. First, synchronized zooplankton abundance and water current HTKE measures were used to determine breakpoints at the confluence of the two wind fetches off Windy Point. Second, additional transect data collected in the same area during previous sample seasons was used to augment the 10 transects from this study and provide zooplankton abundance measures to test patchiness and distributions under different wind conditions.
**Breakpoints in the spatial distribution of zooplankton:**

Windy Point was the location of interest of this study, as previous work by Blukacz (2007) identified it as an area that contained increased variability in zooplankton concentrations and water temperature. It is our goal to link small-scale water current patterns with zooplankton distributions by identifying breakpoints in water turbulence measures and zooplankton densities along a transect centered on Windy Point. We hypothesized that breakpoints in zooplankton concentration and water turbulence (HTKE) would occur near Windy Point, as a result of two converging wind fetches and their associated currents. In order to identify abrupt changes in zooplankton concentrations and turbulence measurements, the Moving Split Window Technique (MSWT) was used. It is an intuitive method of identifying breakpoints and is ideally suited for spatially and temporally changing measurements, such as the transect data in this study (Panis and Verheyen, 1995; Cornelius and Reynolds, 1991; Zalatnai and Kormoczi, 2004).

The Moving Split Window Technique was originally developed by soil scientists seeking to identify boundaries along transects (Cornelius and Reynolds, 1991). Its use has since been expanded to a variety of fields including studies in landscape ecology as well as in aquatic ecology (Panis and Verheyen, 1995; Zalatnai and Kormoczi, 2004). The MSWT analysis carried out in this study was based on the procedure outlined by Cornelius and Reynolds (1991). It had five basic steps: 1) place a window of width Q, containing an even number of one-second sampling units at the beginning of a transect, 2) divide the window into two equal halves, 3) sum values of the variable of interest - either zooplankton biomass or water turbulence - on either side of the window, 4) compare the window halves against each other using Squared Euclidean Distance (SED) as a measure of dissimilarity, and 5) move the window along the transect, one distance unit at a time, creating a distance measure for each location along the transect. (Fig. 4)
Fig. 4) An example of Moving Split Window Analysis with Window Size Q = 2 on simplified data. The difference between the half windows are calculated and squared to find the SED value.
\[ SED = \left( \sum_{i=1}^{n} A_i - \sum_{j=1}^{n} B_j \right)^2 \]

where \( A_i \) and \( B_j \) represent variable values at the \( i^{th} \) and \( j^{th} \) position for the two window halves of size \( n=Q/2 \).

The SED measures were then plotted against distance along the transect (m) with peaks representing breakpoints in values of the target variable. Determining appropriate window size is an important part of MSWT analysis. Small windows, the smallest being two sampling units with single samples as window halves, preserve all of the variability but can contain excessive noise. Large windows are effective at eliminating unwanted noise, but can miss important small-scale discontinuities (Cornelius and Reynolds, 1991). In this study various window sizes were examined \((Q = 2, 4, 6, 8, 10, 12, 16, 20, 30)\) to ensure that small-scale variability would not be missed, and important breakpoints could be seen as window size increased.

To help identify statistically significant breakpoints in the data, a Monte Carlo statistical test was added to the MSWT analysis as suggested by Cornelius and Reynolds, (1991). For each transect, the data points were randomized and SED values were recalculated for each sequential observation using MSWT analyses. This was repeated 999 times, to create 999 pseudovalues for each position along the transect. The actual data comprised the 1000\textsuperscript{th} repetition, and was tested against the upper limit of a 99% confidence interval that was determined by identifying the 10\textsuperscript{th} largest pseudovalue in the ordered array of values for each position. Only squared Euclidean distance values from the data that exceeded this limit were considered to be statistically significant. For visual clarity, the 99% confidence interval was then averaged across each
position along the transect and then superimposed on the graph of SED values to visually indicate which peaks were statistically significant. (See Fig. 5a, 5b)

The analyses described above were used to examine each of the transects (n=10) and to determine where any statistically significant breakpoints may exist, for both zooplankton concentrations and water turbulence measures. The criteria for a significant breakpoint include only those peaks that had 99% significant SED values and that persisted for at least two window sizes. This was done to avoid peaks caused by fluctuations due to random noise in the data; in order to ensure the analysis was rigorous and that breakpoints would be ecologically and physically significant. Based on previous observations of increased zooplankton biomass and water temperature variability off Windy Point by Blukacz, (2007), significant breakpoints were expected to be found clustered near the midpoint of the transects. In addition, it is expected that zooplankton concentration breakpoints and HTKE breakpoints will be located in close proximity within each transect, indicating the link between water currents and associated zooplankton distributions occurring at small-scales, on the order of tens of metres.

In order to further characterize the zooplankton distributions, zooplankton variability was calculated on either side of the breakpoints. This was done to examine how the wind blocking feature of Windy Point may be affecting water currents and zooplankton distributions in the west and east sides of the breakpoints. For each of the replicate transects, the breakpoint in zooplankton concentrations with the highest squared Euclidean distance values across multiple window sizes was used to divide the transect into east and west segments. Once significant breakpoints were established, the variability in zooplankton biomass on either side of the breakpoint was quantified using the Coefficient of Variation,
Fig. 5a)  Graph of zooplankton concentrations from west to east for transect #1 on July 8\textsuperscript{th} at 10:47am. Breakpoints in zooplankton concentrations found using Moving Split Window analyses were plotted as dashed lines.

Fig. 5b)  Graph of zooplankton concentrations from west to east for transect #9 on July 9\textsuperscript{th} at 11:47am. Breakpoints in zooplankton concentrations found using MSWT were plotted as dashed lines.
\[ CV = \frac{s}{\bar{X}} \]

where \( s \) is the standard deviation and \( \bar{X} \) is the sample mean of the data series. The Coefficient of Variation is a unitless measure of relative variability that can be used to effectively compare variability between two data sets, even if the means are different. A paired student’s t-test was used to test for significance between CVs for the east and west sides of all replicate transects. A higher CV represents greater variability of the values for that data set, and a lower CV represents less variability of the values. To test which side of the transects has higher water turbulence, average HTKE measures on either side of the breakpoints were compared using a paired student’s t-test for each transect. It was expected that east of the breakpoints in the open, less protected part of the South Arm, there will be increased turbulence measures, and decreased variability in zooplankton concentrations, due to the mixing effect of the increased water turbulence caused by the higher wind velocities.

**Wind Conditions:**

In previous work, Blukacz (2007) identified three different wind conditions under which different zooplankton patterns arose. In order to quantify wind-induced water currents set-up in the epilimnion, we used a dimensionless Froude number, which compares the inertial forces of internal waves, created by wind force, to the buoyancy forces set up due to vertical temperature microstratification through the epilimnion (Loewen et al., 2007; P. Pernica and M. Wells, Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.). The correlation between wind speeds and current regimes using the Froude number,
would allow us to identify distinct wind conditions that create different current profiles under which zooplankton distributions may vary. Froude number:

$$Fr = \frac{U}{\sqrt{gh \Delta \rho / \rho}}$$

where $U$ is the average horizontal water velocity (m s$^{-1}$), $g$ is the gravitational constant (m s$^{-2}$), $h$ is the depth of the epilimnion (m) and $\Delta \rho$ is the water density difference between the top and the bottom layer of the epilimnion and $\rho$ is the water density at the depth of measurement.

The Froude number has been used to characterize turbulence and mixing in Lake Erie (Loewen et al., 2007), and was implemented to identify wind regimes that cause different water current patterns in Lake Opeongo (P. Pernica and M. Wells, Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.). Using the ADCP measurements as well as vertical water temperature profiles, P. Pernica and M. Wells, (Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.) identified three wind conditions that differed slightly from initial observations by Blukacz (2009), which would create different water current regimes corresponding to particular ranges of Froude numbers. The three wind groups are: $<$3 m s$^{-1}$, 3-6 m s$^{-1}$ and $>$6 m s$^{-1}$. In cases where wind force is low ($<$3 m s$^{-1}$), Froude numbers were found to be lower than 1. These were representative of low current velocities that do not influence the density gradient; little or no current is formed and the weak thermal microstratification remains. Wind speeds of 3-6 m s$^{-1}$ were correlated with the critical Froude number of 1, where inertial and buoyancy forces were in balance and internal waves were predicted to form in the epilimnion. There was sufficient energy to form the downwind water currents as described in the conveyor-belt hypothesis (Ragotzkie and Bryson, 1953; Thackeray et al., 2004), but not so much as to overwhelm the vertical water density gradient and lead to shearing between microstratified temperature layers of
the epilimnion. Froude numbers greater than 1 indicate current velocities high enough to overwhelm the water density gradient, which leads to shearing between microstratified water layers, high turbulence and mixing. Wind speeds above 6 m s\(^{-1}\) were correlated with a Froude number >1, where high turbulence, shearing and mixing of the epilimnion dominate.

Based on the findings by both Blukacz (2007) and Pernica and Wells, (Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.) it was hypothesized that the three different wind regimes would produce distinctive spatial patterns of the zooplankton. First, under low wind conditions with Froude numbers below 1, zooplankton should be fairly homogenously distributed, with small-scale patterns in variability primarily guided by biological interactions. This would be represented by low variability in zooplankton concentrations and small patch sizes due to limited mobility of the zooplankton. Second, persistent winds between 3 and 6 m s\(^{-1}\), with Froude numbers around 1, should present the greatest variability in zooplankton concentrations along the entire transect. Moderate patch sizes were expected as the zooplankton patterns would be shaped by the entrainment along internal waves created by water currents as zooplankton are passively transported downstream (P. Pernica and M. Wells, Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.). Finally, under high wind conditions and Froude numbers greater than 1, the overwhelming turbulence and mixing caused by the increased wind energy should produce well mixed, low variability zooplankton distributions. Zooplankton patchiness should not be present as the mixing should overwhelm any possible biotic interactions or water current distributions.

In order to obtain transects under all three wind conditions, the 10 transects from July 2008 were combined with transect data from the summers of 2001 and 2003. Transects were selected when
the prevailing wind velocities (m s\(^{-1}\)) averaged over both 8 and 24 hours prior to the end time of the transect fell into one of the defined wind speed groups (George and Edwards, 1976; Blukacz, 2009). Prevailing wind conditions were consistently from the west-southwest during the transects, and wind groups were based on wind speeds. A total of 22 transects were chosen, the 10 transects from 2008 all fell into the intermediate wind condition, and 12 additional transects were chosen, 5 in the low wind condition, 4 in the medium wind condition and 3 in the high wind condition. The 12 additional transects used here were segments of longer original transects that had been truncated to span the same area as the 2008 transects, 1 km on either side of the location of interest, Windy Point. First, coefficient of variation (CV) was calculated to determine overall variability of zooplankton concentrations along the whole transect for each of the three different wind conditions. These CV values were then compared using an ANOVA and followed up by post-hoc Tukey’s test to identify potential differences among wind groups.

Assumptions of normality were tested using the Levene’s test for equal variances and the Anderson-Darling test for normality of residuals, and were found to hold.

Second, Geary’s C was used to examine spatial autocorrelation, which is the similarity between closely spaced observations as compared to observations that are spaced further apart (Dale and Fortin, 2002). Positive spatial autocorrelation occurs when neighbouring observations (defined by each distance class) are more closely related than expected by a random distribution. Geary’s C is a measure of spatial autocorrelation for various distance classes that is similar to Moran’s I but is less sensitive to differences in the mean among distance classes. It can be calculated for a given distance class by:
where $n$ is the number of observations in the sample transect, $y_i$ and $y_j$ are the $i^{th}$ and $j^{th}$ observations, $w_{ij}$ is a weighting function that equals 1 when the distance between $y_i$ and $y_j$ is in the distance class $d$, and 0 otherwise, and $W$ is the sum of $w_{ij}$ (the number of observation pairs in distance class $d$). In order to reduce the influence of any large-scale patterns such as a continuous increase in zooplankton biomass along a transect, biomass values were detrended by fitting a straight line to the data and computing Geary’s $C$ from the residuals. In this study, spatial autocorrelation was evaluated at 100 discrete distance classes \{0-3 m, 3-6 m, 6-9 m ...297-300 m\}; the largest being less than $1/4$ the distance of the total transect length in order to avoid problems with the test statistic becoming overestimated. Geary’s $C$ value is always positive, with values of 1 representing distance classes with no spatial autocorrelation, values below 1 indicating positive spatial autocorrelation and values greater than 1 indicating negative spatial autocorrelation. Correlograms can be created by plotting Geary’s $C$ against distance class, and can be used to determine whether the zooplankton distributions were random and well mixed, or whether they exhibited a more heterogeneous, patchy distribution. In order to use a correlogram to estimate patchiness, a significance test must first be completed to ensure that the Geary’s $C$ values are significant in at least one location (Fortin and Dale, 2005). In this case, a randomization procedure was once again used, similar to that for significance testing of the MSWT analysis. A 95% confidence band was created by randomizing the biomass values and calculating pseudoreplicate Geary’s $C$ values for 999 permutations. Each distance class had 999 randomized Geary’s $C$ values along with the real Geary’s $C$ value; the 25$^{th}$ and 975$^{th}$ values were
used to create the lower and upper levels of the confidence interval respectively. A correlogram with at least one significant C value can then be interpreted to determine patchiness and patch size (Fortin and Dale, 2005).

If a correlogram has no spatial autocorrelation, the values of Geary’s C should remain near 1 for all distance classes, have few or no significant C values, and this is indicative of a random, well-mixed distribution. (Fig. 6a, 6b) If a correlogram contains one or many significant Geary’s C values, shows positive spatial autocorrelation at small distance classes, a shift towards no spatial autocorrelation and finally negative spatial autocorrelation as the distance class increases, this indicates that there is heterogeneity and patchiness in the data set. This can even be taken a step further, as another feature of Geary’s C is the ability to estimate patch size. Patch radius would be equal to the first distance class where Geary’s C of the residuals equals 1, representing the distance at which there is no longer any spatial autocorrelation (Legendre and Fortin, 1989; Menza, 2003). (Fig. 7a, 7b) The patch radius in metres could then be determined by multiplying the distance class by 3 m, the length of each distance class.

It was predicted that well mixed transects, (high wind speeds, Froude number > 1) would be identified by a low CV of zooplankton concentrations (representing low overall variability), as well as Geary’s C values that remain around a value of 1, representing no spatial autocorrelation for the various distance classes. More heterogeneous transects with greater zooplankton patchiness, (intermediate wind speeds, Froude number = 1) would be identified by high CV of zooplankton concentrations, and Geary’s C values that vary from high spatial autocorrelation to low spatial autocorrelation from smaller to larger distance classes. For transects that show heterogeneity, patch size was determined using the method outlined above. At low wind speeds, Froude number < 1, biological interactions should dominate, and CV values should be low, with
Fig. 6a) Generated data of randomized values between 0 and 100, n=500 observations, used to plot correlogram of Geary’s C values for a random distribution

Fig. 6b) Example correlogram of Geary’s C values calculated on a random data set (Fig. 5a), indicating C values that remain constant around 1 at all distance classes, indicating no spatial autocorrelation.
Fig. 7a) Generated data of a randomized sine wave: period = 100, n=500 observations, used to plot a correlogram of Geary’s C values.

Fig. 7b) A correlogram of Geary’s C values calculated on a data set based on a sine-wave function, with random variation included, of n=500 observations and a period of 100 (Fig. 6a). The patch radius can be determined by selecting the distance class where the C value first reaches 1. In this case the patch radius is distance class 25.
Geary’s C correlograms indicating small patch sizes due to the limited mobility of the zooplankton.

Results:

Breakpoint Analysis: Moving split window analysis revealed statistically significant breakpoints in zooplankton concentrations for all 10 transects. Significant breakpoints were identified by SED values that were above the 99% confidence interval determined by the Monte Carlo test, and persisted in at least two of the window sizes. (Fig. 8a, 8b) Statistically significant breakpoints were also found for turbulence (HTKE) measures in all 10 transects; there was some degree of spatial overlap between zooplankton and turbulence breakpoints, indicating that they are both occurring in the same general area (Table 1). 81% of zooplankton concentration breakpoints and 92% of turbulence breakpoints were found within 500 metres of the midpoint of the transect, the location of interest, Windy Point. (Fig.9) Statistically significant breakpoints for both zooplankton concentrations and water turbulence were also found east of the midpoint, extending into the East part of the South Arm. Only one turbulence breakpoint and no zooplankton breakpoints were found in the more sheltered, westernmost 500 metres of the transect. These results support the hypothesis that at Windy Point there is a change in the water current pattern that induces a change in zooplankton patterns, although, due to the variability that occurs from one transect to the next, interpretations must be made with some caution.

The paired student’s t-test on the coefficients of variation for the east and west segments of the transect found relatively small, yet statistically significant differences in variability between zooplankton concentrations, on either side of the breakpoints (t=-4.28, p=0.002). The mean CV
Fig. 8a)  MSWT analysis for transect #4, July 8\textsuperscript{th} 15:05, at Window Size (Q) = 8. Significant peaks were identified by the 99% confidence interval shown running horizontally across graph. Note, moderate noise due to relatively small window size.

Fig. 8b)  MSWT analysis for transect #4, July 8\textsuperscript{th} 15:05, at Window Size (Q) = 12, Significant peaks were identified by 99% confidence interval shown on graph. Noise reduced at slightly larger window size.
Table 1) List of transects from July 2008 with GPS coordinates (decimal degrees notation) of all significant breakpoints for zooplankton concentration and turbulence (HTKE) measurements.

<table>
<thead>
<tr>
<th>Transect #</th>
<th>Transect Date/Time</th>
<th>Zooplankton Breakpoint Coordinates</th>
<th>Turbulence Breakpoint Coordinates</th>
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Fig. 9) A graphical representation of zooplankton and turbulence breakpoints from west to east for the 10 transects sampled during July, 2008. Windy Point is situated at the 1000 m position, 81% of zooplankton concentration breakpoints and 92% of turbulence breakpoints were found within 500 metres of Windy Point. There are several transects in which zooplankton and turbulence breakpoints overlap within metres of each other, although this is not consistent for all transects.
for the west side was 0.208 and the mean CV for the east side was 0.238. (Fig. 10) The paired student’s t-test on the average turbulence measures, (Fig. 11), also showed significant differences between the east and west of breakpoint groups (t=3.23, p=0.010). Horizontal turbulent kinetic energy data showed consistent results through the 5 m depth range over which ADCP data was acquired, and the HTKE measures at the OPC opening were consistent with those over the rest of the water profile sampled by the ADCP. The mean HTKE measures on the east side of the transect were 0.0457 m$^2$s$^{-2}$, and the measures on the west side were 0.0413 m$^2$s$^{-2}$. This is evidence that there is significantly higher water turbulence on the east side of the transects. These results were also supported by a comparison of HTKE measures east and west of Windy Point, recorded by P. Pernica and M. Wells (Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.)

**Wind Conditions:** Coefficients of variation were calculated for zooplankton concentrations for each of the 22 transect replicates in the combined data set. There were significant differences among coefficients of variation for each of the wind speed groups (Single-factor ANOVA, $[F_{(2,19)}= 7.71, p = 0.004$]). A post-hoc Tukey test showed that zooplankton concentration in the 3-6 ms$^{-1}$ wind speed group had significantly higher CV (mean=0.24) than the low wind speed group (mean=0.19) (p=0.004), the low and high wind speed group did not differ significantly in CV (p=0.71), and although the 3-6 m s$^{-1}$ group also had higher CV than the high wind speed group (mean=0.20), the difference was not significant (p=0.12). (Fig. 12)

These results support the hypothesis that variability in zooplankton concentrations were highest in the medium (3-6 m/s) wind group. The low variability of zooplankton concentrations in the low wind group was also expected as under low wind conditions biological interactions dominate, and these would produce limited variability due to movement restrictions of
Box plot of differences of a paired student’s t-test, showing 95% t-confidence interval for the mean, comparing Coefficient of Variation between zooplankton distributions west (mean=0.2080) and east (mean=0.2380) of the breakpoints. The null hypothesis (differences = 0) was rejected as significant differences were found between mean Coefficients of Variation of the two groups (t= -4.28, p= 0.002).
Box plot of differences of a paired student’s t-test, showing 95% t-confidence interval for the mean, comparing HTKE measurements between zooplankton distributions west (mean=0.0413) and east (mean=0.0457) of the breakpoints. The null hypothesis (differences = 0) was rejected as significant differences were found between HTKE measurements of the two groups (t=3.23, p=0.01).
Box plot of ANOVA comparing Coefficient of Variation between the three wind speed groups: High Wind (> 6 m/s; mean = 0.201), Low Wind (<3 m/s; mean = 0.186) and Moderate Wind (3-6 m/s; mean = 0.237). Significant differences, evaluated by a Tukey’s test and indicated by $a$ and $b$ notations, existed only between low and moderate wind speed groups.
zooplankton. The high wind group also had low variability, as expected, because turbulent mixing associated with Froude numbers above 1 should have a homogenizing effect on zooplankton distributions and reduce the overall variability. Although the results were not statistically significant between the medium and high wind conditions, the trend is visible, and the lack of significance may simply be due to low power associated with the relatively small sample sizes.

Results from the Geary’s C analysis of the high wind, high Froude number transects showed very little spatial autocorrelation between distance classes, and correlograms showed C values close to 1 indicating no spatial structure in zooplankton biomass. (Fig. 13) Significance testing revealed few significant C values for each of the transects, reinforcing the randomized nature of the data. These results support the hypothesis that high winds lead to mixing throughout the epilimnion (reflected in Froude numbers > 1), which reduce zooplankton patchiness. The lack of positive spatial autocorrelation even at small distance classes indicated that there was no identifiable patch structure. For the moderate wind condition, Froude number = 1, correlograms showed Geary’s C values that were consistently below 1 for small distance classes, indicating positive spatial autocorrelation, and increased as the distance classes increased towards the maximum. (Fig. 14) Significance testing found many Geary’s C values to be significant in each transect, for both positive and negative autocorrelation at small and large distance classes respectively. These results fulfill the requirement for significant C values to be found in order to use the correlograms to analyze patch size. In the low wind, low Froude number condition, Geary’s C values were also below 1 at small distance classes and generally increased at further distance classes. (Fig. 15) Significance testing again found many C values to be significant, and patch size was examined.
Fig. 13) Correlogram of Geary’s C values for zooplankton concentrations from a high wind condition transect on July 5\textsuperscript{th}, 2001 at 14:31. An over plot of the 95\% confidence intervals showed few significant Geary’s C values, which fluctuated around 1, similar to a random distribution.
Fig. 14) Correlogram of Geary’s C values for zooplankton concentrations from a moderate wind condition transect on September 13th, 2003 at 12:37. An over plot of a 95% confidence interval indicated Geary’s C values with significant positive spatial autocorrelation at small distance classes. Patch size radius, indicated by the arrows, occurred when spatial autocorrelation first became absent (C value = 1, Distance class = 33). Spatial autocorrelation then became increasingly more negative as distance classes became larger.
Fig. 15) Correlogram of Geary’s C values for zooplankton concentrations from a low wind condition transect on July 9\textsuperscript{th}, 2001 at 11:12. An over plot of a 95% confidence interval indicated Geary’s C values with significant positive spatial autocorrelation at small distance classes. Patch size radius, indicated by the arrows, occurred when spatial autocorrelation first became absent (C value = 1, Distance class = 27). Spatial autocorrelation then became increasingly more negative, peaking at significant C values of 1.4, before decreasing to no spatial autocorrelation and finally significant positive spatial autocorrelation at the largest distance classes.
Patch sizes were significantly different between low and moderate wind speeds (Student’s two-sample t-test, $t = 3.31$, $p=0.005$, df=15), with low wind having smaller patches (mean= 29$^{th}$ distance class, 87m) than moderate wind speed (mean= 52$^{nd}$ distance class, 156 m). (Fig. 16) This may be an indication of biological interactions acting over a smaller scale at the low wind speeds, whereas current forces acting on a larger scale influence the spatial patterning of zooplankton at moderate wind speeds and a Froude number of 1.

**Discussion:**

*Breakpoints:* Blukacz (2007) had previously identified areas of increased variability in temperature and zooplankton biomass off Windy Point, Lake Opeongo, Ontario and suggested that these changes in variability were a function of prevailing wind speeds. However, without current data, it was impossible to characterize the physical and/or biological processes that caused such variation. The simultaneous zooplankton and water current information afforded by the use of the OPC and ADCP in synchrony has provided us with a novel way to approach this question. Moving-split window analysis confirmed our initial hypothesis there are significant breakpoints in zooplankton concentrations in the area off Windy Point. Significant breakpoints in water turbulence were also found with varying degrees of overlap with the zooplankton breakpoints. Although the overlap between the turbulence and zooplankton breakpoints varied among transect replicates, occurring in a range of metres apart to hundreds of metres apart, breakpoints in both the biological and physical variables were clumped in an area near the midpoint of the transect adjacent to Windy Point. Breakpoints were also found east of this region, but very few were found in the more sheltered section of the transect to the west of
Fig. 16) Box plot showing results of a student’s t-test comparing Patch Size Radius between zooplankton distributions in moderate (mean=52.1) and low (mean=29.2) wind speed groups. Significant differences were found for mean patch sizes between groups (p=0.005, df=15).
Windy Point. As was previously noted by Blukacz (2007), the high elevation of Windy Point is a southerly wind-blocking feature in the South Arm on the West side of Windy Point. The surface topography of Windy Point creates an area in the South Arm where two wind fetches converge, and under appropriate wind conditions, there is some evidence that this area features the confluence of two near-surface currents. The prevailing wind speeds recorded over the sampling period in July, 2008 were between 3-6 m s\(^{-1}\), indicating that they were in the range corresponding to a Froude number of 1 where currents would form in the epilimnion. Breakpoints in zooplankton abundance and water turbulence are evidence that water current patterns created by prevailing winds and local topography may be an important factor in shaping small-scale zooplankton distributions. The convergence of two water currents is the likely physical factor responsible for the observed zooplankton distributions associated with Windy Point.

The analysis of spatial heterogeneity on either side of Windy Point showed significantly greater zooplankton variability on the east side of the transects. Although the results were statistically significant it is important to address the relatively low difference between the mean CVs of the east (0.238) and west (0.208) segments. The CV values represent a look at overall variability for each transect half, and small differences may still have important ecological implications. Lake Opeongo is an oligotrophic lake, characterized by low nutrients and low overall productivity. This means that at every trophic level, foragers must optimize their feeding. Therefore, despite small changes in relative variability of zooplankton distributions, these results can still indicate patchiness that is potentially important for interactions between various trophic levels.

The east side of the transects also showed evidence of high turbulence, as Horizontal Turbulent Kinetic Energy (HTKE) measures were found to be significantly higher on the more open, east
side of the transects. Pernica and Wells (Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.) also showed similar results along transects recorded on different dates, finding significant differences in HTKE when comparing the west and east sides of the transect, with the east section having a higher HTKE. These results contradicted our predictions, as it was expected that increased wind energy would lead to increased turbulence and mixing in the water column which would create a more randomized distribution of zooplankton and a lower associated variability. Instead, we found that east of windy point, increased water turbulence was associated with an increase in zooplankton variability compared to the more sheltered west side of the transects.

One possible explanation of this is that east of Windy Point there are downwelling or upwelling areas where the two water currents converge. Personal observations of wave action during the 10 transects found it to be minimal west of Windy Point, and it followed the prevailing westerly wind. Once past Windy Point, there was a noticeable change in wind speed and direction, with the convergence of the westerly wind with a southerly wind from Sproules Bay. This increase in wind energy led to increased wave height, surface wave convergence and a change in the direction of the waves, which now followed the southerly wind. (Bridgeman, Personal Observation). It is possible that the converging currents created complex water profiles with downwelling currents that led to increased zooplankton patchiness and variability in the presence of increased water turbulence.

Another possible explanation follows observations by Blukacz, (2009) that Langmuir circulation may be responsible for the observed small scale variability. Langmuir circulation is the formation of helical currents rotating in opposite directions and running parallel to the direction of the wind when a sufficient wind force is applied to the surface of the water (Stavn, 1971,
The helices are spaced evenly at a distance of approximately the epilimnion depth, and create alternating upwelling and downwelling zones where two helices converge. These upwelling and downwelling currents can be identified by lines of foam at the surface running perpendicular to the wind direction, and have been shown to be important factors shaping small scale zooplankton distributions (Stavn, 1971, Blukacz, 2009). North-south oriented surface foam lines were present in the open part of the South Arm, east of Windy Point, during our sample transects. These lines indicated that the southerly wind was the cause of the Langmuir helices, which explained why no Langmuir circulation was evident west of Windy Point. It is possible that Langmuir circulation was responsible for some of the small scale zooplankton variability, as the sample transect ran perpendicular to the upwelling and downwelling currents, and OPC measurements may have been crossing through alternating upwelling and downwelling currents.

**Wind Conditions:** Froude number was an important tool used to characterize water current profiles under three different wind conditions (Loewen et al., 2007; Pernica and Wells, Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.). Based on observations by Blukacz, (2009) we were able to identify the low, moderate and high wind conditions that correlated with Froude numbers less than 1, equal to 1 and greater than 1, respectively (Pernica and Wells, Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Pers. Comm.). Under moderate wind speeds, inertial forces and buoyancy forces were in balance and water currents running in the direction of the prevailing wind were expected to form. These currents would entrain zooplankters downwind, thus supporting the conveyor-belt hypothesis (Ragotzkie and Bryson, 1953; Thackeray et al., 2004; Loewen et al., 2007; Pernica and Wells, Physical and Environmental Sciences, University of...
Toronto Scarborough, Toronto, ON, Pers. Comm.). It was under these conditions that increased patchiness and heterogeneity of zooplankton distributions were expected to occur, due to the entrainment of zooplankton along internal waves of the surface current. Under moderate wind speeds (3-6 m s\(^{-1}\)), significantly higher spatial heterogeneity in zooplankton concentrations were found when compared with low wind speed (<3 m s\(^{-1}\)) condition, and heterogeneity for the moderate group was also higher than the high wind speed group (>6 m s\(^{-1}\)) although not significantly so. These results were consistent with the hypothesis that under moderate winds, wind-induced current forces would lead to increased variability and increased heterogeneity of zooplankton distributions. Variability did not differ significantly between the high and low wind speed group, which was expected as these groups should show less heterogeneous distributions. These low variability distributions, however, were expected to occur due to different processes. In the low wind speed group, zooplankton biological processes were expected to dominate in the absence of water currents. Coordinated movements such as swarming behaviour for feeding on phytoplankton or evading predators would be limited by the low motility of zooplankton, producing distributions with smaller patches and low variability. In the high wind speed group, turbulence and mixing is expected throughout the epilimnion, and this would completely overwhelm and biological processes and have a randomizing effect on zooplankton distributions, causing a low variability. These results were seen using the Geary’s C analyses, which provided more important information about the zooplankton distributions than the coefficients of variation. Under high winds, inertial forces overwhelm buoyancy forces, as is expressed by a Froude number > 1, thus creating turbulence and mixing throughout the epilimnion. With little or no spatial autocorrelation present even at small distance classes, patches were not representative features of the zooplankton distributions.
Geary’s C values for both the low and moderate wind speed groups showed statistically significant positive spatial autocorrelation at small scales, with significant negative spatial autocorrelation at large scales. This was evidence that under both of these conditions, zooplankton distributions were heterogeneous, with patches being important parts of the spatial structure. In the case of the low wind condition, patch size was significantly smaller than the moderate wind condition. This was evidence that at low wind speeds small patches may be due to biological interactions such as predation on chlorophyll or predator avoidance behaviour. At moderate wind speeds, patch sizes were significantly larger, suggesting that physical forces such as internal waves may be driving the spatial patterning of zooplankton distributions.

These results fit with the ‘multiple driving forces’ hypothesis introduced by Pinel-Alloul (1995). Large scale patterns are generally created by physical forces such as wind-induced water currents, whereas biological interactions may dominate smaller scales, especially if wind forces are unimportant.

**Conclusion:** We were able to identify breakpoints at Windy Point for both biological and physical variables using MSWT analysis. By combining breakpoints in HTKE measures with personal observations and historical wind data (Finlay et al., 2001, Blukacz, 2007) we found evidence that wind-induced water currents were converging on the east side of Windy Point. More importantly, breakpoints were also identified in zooplankton concentrations occurring in the area of Windy Point, indicating that the converging water currents may be responsible for the small scale patchiness in zooplankton distributions found in this area, as was predicted by our hypothesis.
Two mechanisms have been proposed to be contributing to the zooplankton patchiness. Converging currents massing water off Windy Point may be creating downwelling and upwelling sites that have previously been proposed to contribute to zooplankton patchiness (George and Winfield, 2000; Thackeray et al., 2004; Rinke et al., 2007). These results are in accordance with observations made by Blukacz, (2009) where zooplankton and water temperature variability increased in the area off Windy Point, especially under moderate wind conditions. The second possible explanation is that in the open part of the South Arm, east of Windy Point, a strong southerly wind created Langmuir circulation patterns and associated upwelling and downwelling sites that increases the variability in zooplankton distributions in this area. In both cases, wind-induced water current patterns were shaping small scale zooplankton distributions in the area of Windy Point.

The area off Windy Point may have an important ecological function for interaction between trophic levels in Lake Opeongo. If under moderate wind conditions, zooplankton aggregations commonly form off Windy Point, this may be an important foraging area for the local zooplankton predator, the Lake Cisco. The importance of zooplankton aggregations, caused by wind patterns, on trophic interactions have already been shown by George and Winfield (2000), and topographical features shaping wind patterns are another potential source of zooplankton patchiness at the smaller scale. Local aggregations can have important trophic implications; fish that prey upon zooplankton can optimize feeding by targeting passively transported prey patches, as was found in Loch Ness, where fish concentrations were found to be elevated in areas of known zooplankton aggregations due to downwelling sites (George and Winfield, 2000).

We were able to successfully characterize three different wind conditions and their associated current regimes. Through our analyses of CV and Geary’s C values, we were able to determine
that high wind conditions result in a more homogenized distribution, and low wind conditions result in more biologically dominated patterns, with small patch sizes. Moderate wind regimes resulted in the most heterogeneous distributions, with largest patch sizes, which followed our hypothesis and fit the ‘conveyor-belt hypothesis’ proposed by Pinel-Alloul (1995).

This study shows the value that coordinated, fine-scale biological and physical measurements afforded by the OPC and ADCP, can further our understanding of processes affecting zooplankton distribution in lakes. As zooplankton are an important link between primary producers and fish communities, better understanding their distribution is critical to better understanding lake ecosystems as a whole. The identification of topographical features being an important component of small-scale zooplankton patterns can certainly be applied to other lake systems, especially those that contain an important peninsula such as Windy Point that create unique wind patterns. These small-scale patterns could directly affect passively transported zooplankton and phytoplankton distributions, but also indirectly effect fish species distributions through trophic interactions.

Future work is certainly required to better tease apart the effects of biotic and abiotic processes seen in this study. Replication of this study in other lakes, as well as a combining zooplankton and current measures from this study with hydroacoustic fish sampling could help identify the potential importance of local topography and wind patterns on trophic interactions. Using a greater sample size of transects that were evenly distributed across all three wind conditions would be paramount for further insight. In addition, MSWT analysis used in this study, and Wavelet analysis, used by Blukacz (2009) should be compared to see if breakpoints overlap.
References:


Appendix:

The following figures include the zooplankton concentrations and HTKE measurements along the 10 transects in July 2008. Transect information is provided in a table above each of the sample transect, which includes: transect number, date, start time, as well as average wind speeds 8 and 24 hours prior to the end of the transects, and the direction of the wind at the beginning of the transects. The equations for the detrended data are also included, with the associated coefficient of determination.
<table>
<thead>
<tr>
<th>Transect #</th>
<th>1</th>
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</thead>
<tbody>
<tr>
<td>Date/Start Time</td>
<td>July 8th, 2008 10:47 am</td>
</tr>
<tr>
<td>Average Wind Vel. (8 hr)</td>
<td>3.11 m/s</td>
</tr>
<tr>
<td>Average Wind Vel. (24 hr)</td>
<td>3.39 m/s</td>
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<tr>
<td>Wind Direction at Start</td>
<td>204.1°</td>
</tr>
<tr>
<td>Linear Detrending Eq.</td>
<td>( y = 0.0158x + 1349.1 )</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.0009</td>
</tr>
</tbody>
</table>

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**Graph 1:** Zooplankton Concentration (µg/L) vs. Time (s)

- X-axis: Time (s) from 1 to 2001
- Y-axis: Zooplankton Concentration (µg/L) from 0 to 3000

**Graph 2:** HTKE (m²/s²) vs. Time (s)

- X-axis: Time (s) from 0 to 1500
- Y-axis: HTKE (m²/s²) from 0 to 0.14

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51
Transect # 2
Date/Start Time: July 8th, 2008
11:27 am
Average Wind Vel. (8 hr): 3.15 m/s
Average Wind Vel. (24 hr): 3.40 m/s
Wind Direction at Start: 206.3º
Linear Detrending Eq.: $y = 0.0072x + 1399.5$
$R^2 = 0.0002$

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[Graph of Zooplankton Concentration vs. Time (s)]

[Graph of HTKE (m²/s²) vs. Time (s)]
<table>
<thead>
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<tr>
<td>Date/Start Time</td>
<td>July 8\textsuperscript{th}, 2008 12:10 pm</td>
</tr>
<tr>
<td>Average Wind Vel. (8 hr)</td>
<td>3.22 m/s</td>
</tr>
<tr>
<td>Average Wind Vel. (24 hr)</td>
<td>3.47 m/s</td>
</tr>
<tr>
<td>Wind Direction at Start</td>
<td>216.5</td>
</tr>
</tbody>
</table>
| Linear Detrending Eq. | $y = 0.0845x + 1260.1$  
$R^2 = 0.0229$ |
Transect # 4

Date/Start Time July 8th, 2008 3:05 pm

Average Wind Vel. (8 hr) 4.75 m/s
Average Wind Vel. (24 hr) 3.59 m/s
Wind Direction at Start 213.1°
Linear Detrending Eq. \( y = -0.0481x + 1163 \)
\( R^2 = 0.009 \)
<table>
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<tbody>
<tr>
<td>Date/Start Time</td>
<td>July 8&lt;sup&gt;th&lt;/sup&gt;, 2008 3:43 pm</td>
</tr>
<tr>
<td>Average Wind Vel. (8 hr)</td>
<td>4.99 m/s</td>
</tr>
<tr>
<td>Average Wind Vel. (24 hr)</td>
<td>3.69 m/s</td>
</tr>
<tr>
<td>Wind Direction at Start</td>
<td>214.0°</td>
</tr>
</tbody>
</table>
| Linear Detrending Eq. | $y = 0.1041x + 1262.2$  
$R^2 = 0.057$ |

![Zooplankton Concentration (µg/L) vs Time (s)](image1)

![HTKE (m³/s²) vs Time (s)](image2)
**Transect #** 6

**Date/Start Time**
- July 8th, 2008
- 4:25 pm

**Average Wind Vel. (8 hr)** 5.12 m/s

**Average Wind Vel. (24 hr)** 3.75 m/s

**Wind Direction at Start** 215.6°

**Linear Detrending Eq.**
- \(y = 0.0205x + 1191.7\)
- \(R^2 = 0.0022\)
Transect # 7
Date/Start Time: July 9th, 2008, 10:22 am
Average Wind Vel. (8 hr): 3.88 m/s
Average Wind Vel. (24 hr): 3.91 m/s
Wind Direction at Start: 216.8°
Linear Detrending Eq.: y = 0.0918x + 1091.7
R² = 0.0705
Transect #

Date/Start Time
Average Wind Vel. (8 hr)
Average Wind Vel. (24 hr)
Wind Direction at Start
Linear Detrending Eq.

8
July 9th, 2008
11:16 am
3.83 m/s
3.92 m/s
213.5°
y = 0.1179x + 1026.1
R² = 0.0561

Zooplankton Concentration (µg/L)

Time (s)

HTKE (m²/s²)

Time (s)
Transect # 9
Date/Start Time July 9th, 2008
11:47 am
Average Wind Vel. (8 hr) 3.78 m/s
Average Wind Vel. (24 hr) 3.93 m/s
Wind Direction at Start 215.0°
Linear Detrending Eq. y = 0.0633x + 1102.6
R² = 0.0267

Zooplankton Concentration (µg/L)

HTKE (m³/s²)

Time (s)
Transect # 10
Date/Start Time July 9\textsuperscript{th}, 2008
12:37 pm
Average Wind Vel. (8 hr) 3.74 m/s
Average Wind Vel. (24 hr) 3.93 m/s
Wind Direction at Start 225.6\degree
Linear Detrending Eq. \( y = 0.0756x + 1176.5 \)
\( R^2 = 0.0276 \)

![Zooplankton Concentration (\( \mu g/L \))](image1)

![HTKE (m\( ^2 \)/s\(^2 \))] (image2)