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Thermal Variability in the South Lake Champlain from 1997-1999

Lake Champlain Basin Program

Prepared by
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for
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Note: the appendices referred to in this report are available separately from the Lake Champlain Basin Program

- Abstract –

Thermal data were collected in the South Lake of Lake Champlain during a period of three years, 1997-1999, from early June to late October. Water level data available for analysis were collected in 1997 and 1999 at Port Henry, NY and Whitehall, NY. Thermal observations varied from 4 to 8 sites evenly distributed along the South Lake. Both deep and surface temperatures were monitored at a nominal sampling rate of 30 minutes. Water level data are consistent at the two sites and were strongly correlated with north-south wind forcing. Surface temperatures had temporal variations ranging from diurnal to interannual. North of Five Mile Point, internal seiche dynamics of the Main Lake were observed as warm pulses of water immediately followed by a hypolimnic internal gravity current. These events are referred to as "thermal hooks" due to their unique signature when plotted. These thermal hook events, which number from 4-6 per observational period per year, were estimated to propagate rapidly past the Crown Point Bridge at maximum speeds of 42 cm/s. When entering shallower water, propagation speed drops rapidly to approximately 8 cm/s. These numbers agree well with observed propagation times from the Crown Point Bridge to Five Mile Point. Past Five Mile Point, these thermal hook pulses can no longer be accurately defined although there might be indications that they did propagate past this site. In 1997, an ADCP was placed at a depth of 6.4 m at the Crown Point Bridge for a period of 2 weeks. Results showed a very dynamic bi-directional velocity of water into and out of the South Lake along with a strong diurnal signal associated with echo intensity, which was believed to be associated with vertical migration of zooplankton or slightly larger species. During this 2-week time period, the velocity structure of a thermal hook event was documented and agreed well with expected current velocities. Spectral and cross-spectral analyses show that the South Lake does have preferred oscillations and that these are of long period (1-7 days) and driven by the atmosphere. Data from the met station at the International Paper Company (1999) showed the inability of the Main Lake met stations (Colchester Reef and Burlington International Airport) to adequately define proper winds conditions existing over the South Lake.

- Project Description –

The scope of this program was to critically investigate the thermal variability and associated forcing functions existing within the boundaries of Lake Champlain known as the South Lake. Specifically, this program was designed to determine the extent of the Main Lake's internal seiche dynamics within the South Lake, lake level variability and potential correlation with atmospheric forcing. This program was also designed to augment the phosphorous monitoring fieldwork that was carried out by Dr. Steven W. Effler of the Upstate Freshwater Institute (Syracuse, NY) during the summer of 1998.

While this hydrodynamic program was designed for the above-mentioned purposes, it should be noted that the observation of currents within the South Lake could not be monitored consistently due to lack of funds. As a result, all parties acknowledged that the results obtained from such a thermally-based observational program could not accurately define water velocity within any region of the South Lake. The thermal observations when combined with lake level variations and atmospheric forcing can only be used to suggest general motion within the water column.

The results presented within this preliminary report covers summertime observations from 1997, 1998, and 1999. Although 1997 data was informally gathered under a no-cost pilot program between NYDEC and Marine Research Corporation (MRC), these data are provided for completeness.

- Introduction -

With an average depth of 2.7 m and width 1.08 km, the South Lake possesses completely different characteristics over its 53 km length than that of the Main Lake which has an average depth and width of 31 m and nearly 7 km, respectively (Meyer and Gruendling, 1979). While the volume of the South Lake comprises only 0.6 percent of the total volume of Lake Champlain (i.e., 0.156 cubic kilometers), its drainage basin of approximately 3000 square kilometers comprises approximately 15 percent of Lake Champlain's total drainage basin (Henson, 1972; Meyer and Gruendling, 1979). From these statistics as well as the use of Figure 1, it can be observed that the South Lake represents more of a river-like environment when compared to the broader reaches of Lake Champlain.

Hydrodynamic research within Lake Champlain over the past 10 years has been a joint effort between MRC, Middlebury College, Lamont-Doherty Earth Observatory (LDEO) of Columbia University, and the NOAA Great Lakes Environmental Research Lab (GLERL). Prior to 1997, this work has been confined solely to the Main Lake between Thompsons Point to the south and Rouses Point to the north. The aim of the program being a better understanding of whole lake water movement, dominant processes that control it, associated forcing functions, and a basic model that represents these dynamics.

Without exception, the internal seiche of the Main Lake, which propagates along the interface between the upper mixed layer (epilimnion) and the deeper cold water (hypolimnion), is the most dynamic feature existing within the lake (Manley et al., 1999). Hidden from view, it rarely has any surface expression, yet it possesses the capability of moving several cubic kilometers of water within the lake every 2-3 days (Manley et al., 1999). The Main Lake, north of Thompsons Point, has been monitored for over five years, yet evidence suggests that the region between Thompson’s Point and the Crown Point Bridge may control a significant amount of the internal mixing found in the lake (Hunkins et al., 1998; Manley et al., 1999).

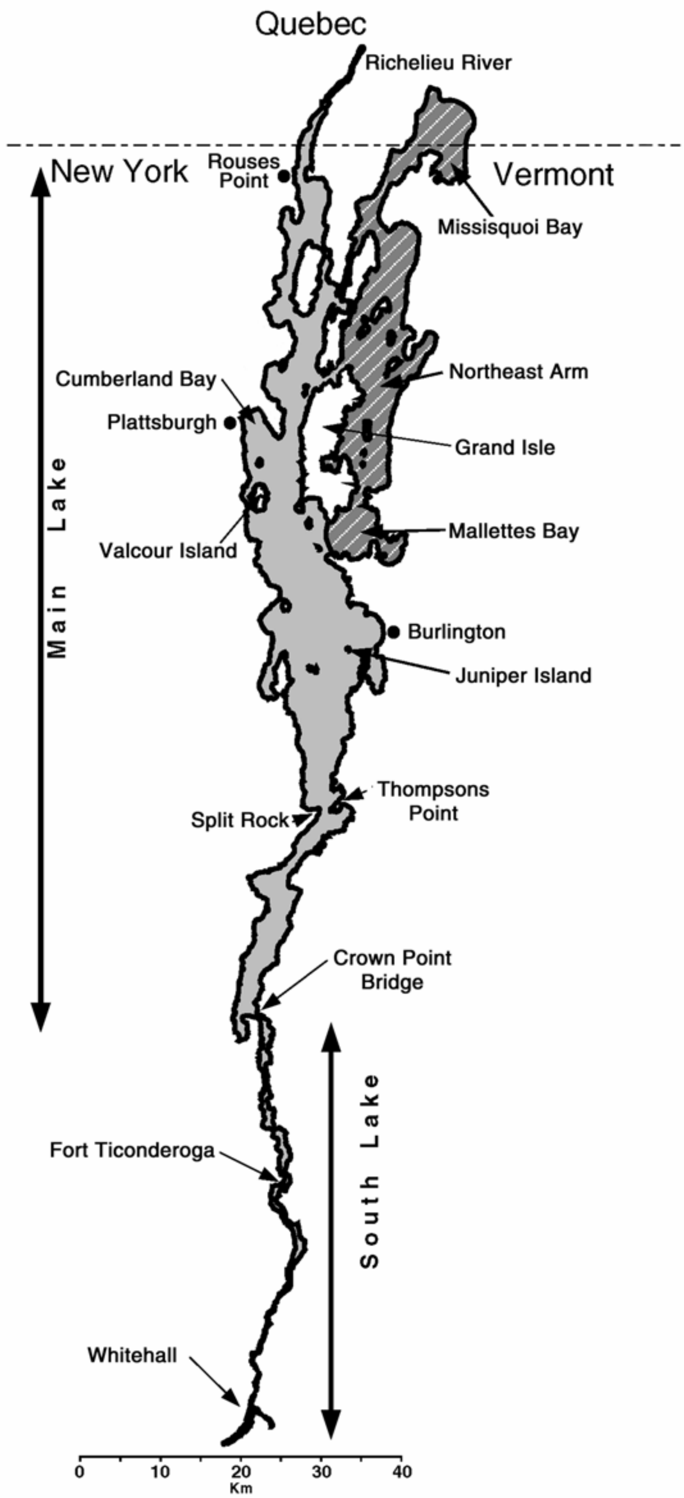

Figure 1. Lake Champlain and its major divisional boundaries (adapted from Manley et al., 1999).

In 1997, NOAA funded a research program within the southern portion of the Main Lake (hereto referred to as the South Main Lake) with specific goals of looking for evidence of a breaking internal seiche, hypolimnic outcropping at the surface, shear instabilities, and sediment resuspension. During this program, eight subsurface moorings were deployed near the end of May (Figure 2). The five 'deepest' moorings were equipped with Acoustic Doppler Current Profilers (ADCP) capable of profiling a majority of the water column, 40 m thermistor chains that spanned the metalimnion, sediment traps, and one bottom photographic system. The three shallowest moorings (closest to the Champlain bridge) were only equipped with temperature probes and sediment traps.

Results from the 1997 South Main Lake program provided many new findings. Klein (1998) observed the presence of both linear and non-linear internal seiche regimes within this region. During strong non-linear events, it was found that the propagation of the deep hypolimnic water formed a steep-walled internal gravity current as it progressed southwards from Potash Point to the Crown Point Bridge. Figure 3 shows the thermal variability of the water column through time at the Mullen Bay and Crown Point bridge sites. For most of the deep hypolimnic cooling events occurring at Mullen Bay (i.e., those green to blue colored pulses in the deep water seen in Figure 3), there is an accompanying event observed at Crown Point after a brief phase lag. What is interesting to note is the change in physical structure of the leading edge of the wave over this distance. The wave front has the appearance of becoming much steeper, almost to the point of being vertical. As a result of these large southerly excursions of deep hypolimnic water into the shallow water regimes directly north of the Crown Point bridge, near surface temperatures were also observed to decrease; due to the removal of warm surface water during these events. Directly north of the Crown Point Bridge, a remnant cold pool of water was found to exist for some time following each one of these southern propagating hypolimnic events.

Analysis of currents within the 1997 South Main Lake data set confirmed those findings of Klein (1998), but additionally presented evidence of a net counter-clockwise circulation existing within the South Main Lake (Osterberg, 1999). Osterberg (1999) further showed that the presence of a second internal vertical mode was most likely the result of northward propagating internal surges created by strong northerly winds that rapidly depressed the metalimnion in the South Main Lake.

South of the Crown Point Bridge (i.e., the South Lake), few hydrodynamic investigations have taken place and of these, all have been short-term and/or spatially restricted. As a result of this general lack of long-term observations within the South Lake, a no-cost cooperative pilot-program between NYDEC and MRC was started in the summer of 1997. While the aim of this study was to gain a better understanding of lake level oscillations and thermal variability as a function of wind forcing, advantage was also taken of the 8 subsurface moorings collecting data just north of the South Lake.

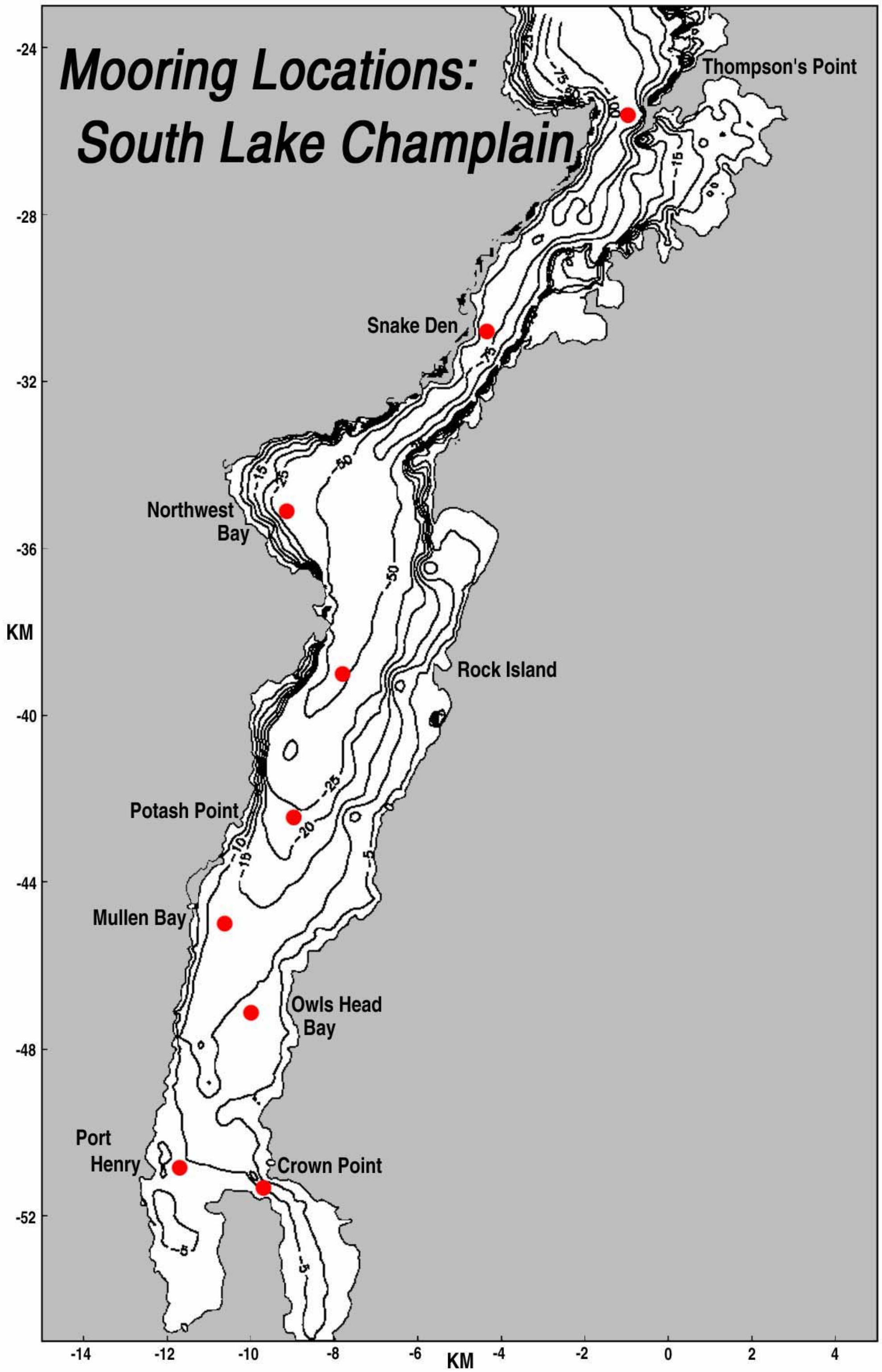

Figure 2. Bottom bathymetric map of the South Main Lake showing the locations of the eight subsurface moorings during the 1997 survey (from Klein, 1998).

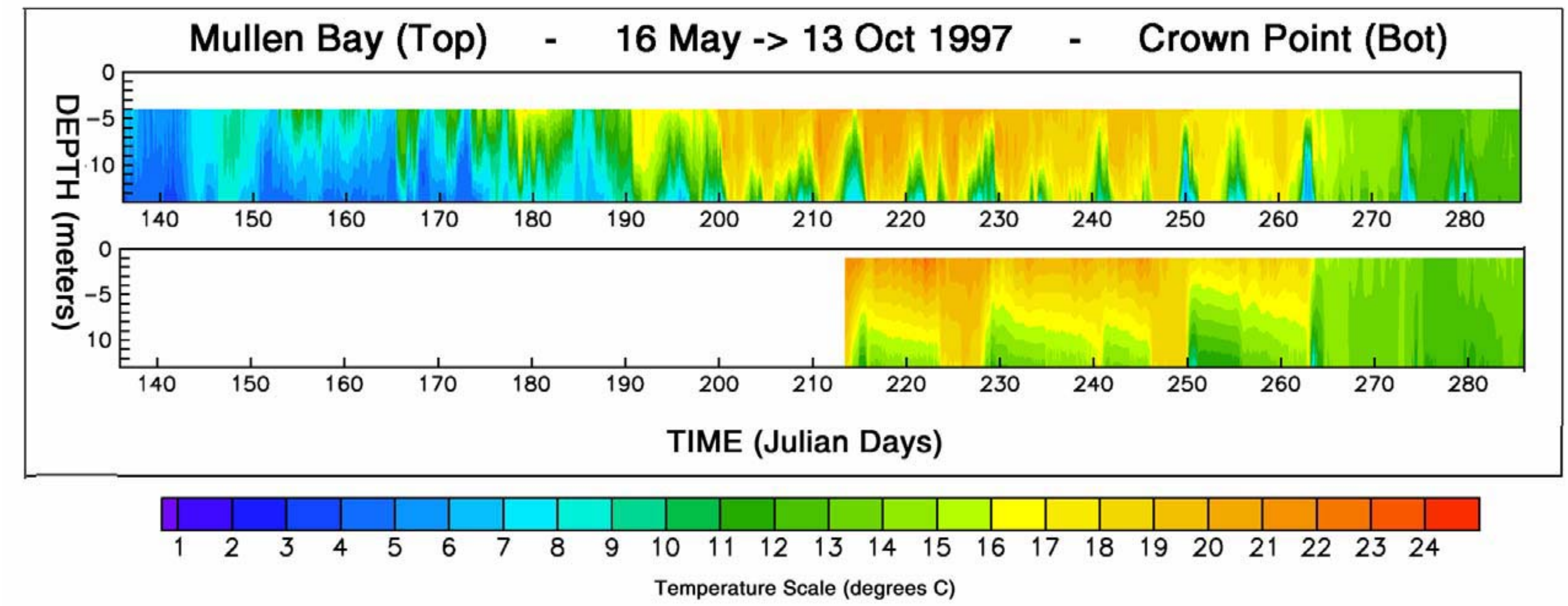

Figure 3. Gridded thermal data from the Mullen Bay and Crown Point bridge sites showing the passage of several internal gravity currents as they propagated southwards. While not all hypolimnic intrusions observed at Mullen Bay propagated southwards to the Crown Point bridge, several large events did. Note that transitional difference in structure of the internal gravity current's leading edge between the two different sites.

- Technical Design of Field Program -

Thermal variability observed at any given site within the lake is a result of a wide range of temporal and spatial forcing functions. These forcing functions can range from seasonal trends, diurnal variations in solar heating, lateral advection from natural (e.g., streams) or man-made inputs (e.g., outfall pipes), and/or rapidly changing internal dynamics within the system to name a few.

Since the focus of this investigation was to determine the effects of both the internal seiche and atmospheric forcing within the South Lake, it was determined that these diverse forcing functions could be easily separated within the data set. Even though the internal seiche is a complicated feature, it can never the less be monitored with very simple temperature sensors. In that the waveform of the internal seiche can be defined as the oscillation of the thermocline (region of the largest vertical temperature change between the epilimnion and hypolimnion) within the lake, then the internal seiche can be defined by rapid temperature changes at any given location. In other words, large changes in temperature observed over a short period of time would tend to indicate the passage of the thermocline (and therefore the internal seiche) through any given point. On the other hand, long-term as well as short-term climatic variations associated with seasonal and diurnal changes can easily be decoupled from those associated with internal seiche dynamics. By placing temperature sensors at predefined locations along the bottom of the South Lake as well as close to the surface, the progression of southward propagating internal gravity currents can be documented.

During the 1997 South Main Lake pilot program, four evenly spaced sites were instrumented based on the location of navigational aids as well as their proximity to the deep center channel. These sites were located at the Crown Point Bridge, Five Mile Point, Benson landing and Whitehall. In subsequent years (1998, 1999), four additional intermediate sites were added. These eight sites, from north to south, were the Crown Point Bridge, Putnam Creek, Five Mile Point, Catfish Bay, Gourlie Point, Benson Landing, Dresden Narrows, and Whitehall. Figure 4 shows the location of these various sites within the South Lake, while Figures 5-11 provide more detailed information as to their location on NOAA maps.

All of the sensors were placed as close to their 1997 starting locations as possible in order to maintain a consistent spatial data set over time. Realistically, variations in spatial positioning could be primarily attributed to the location of the navigational aid used. Frequently, the U.S. Coast Guard services these navigational aids and hence, their repositioning could be slightly off from year to year. In general, it is believed that the location of these temperature sensors during the several years of observations has been within a maximum range circle of 25 meters. Satellite positioning was not required in this particular program because of the consistency by which the U.S. Coast Guard places their navigational aids.

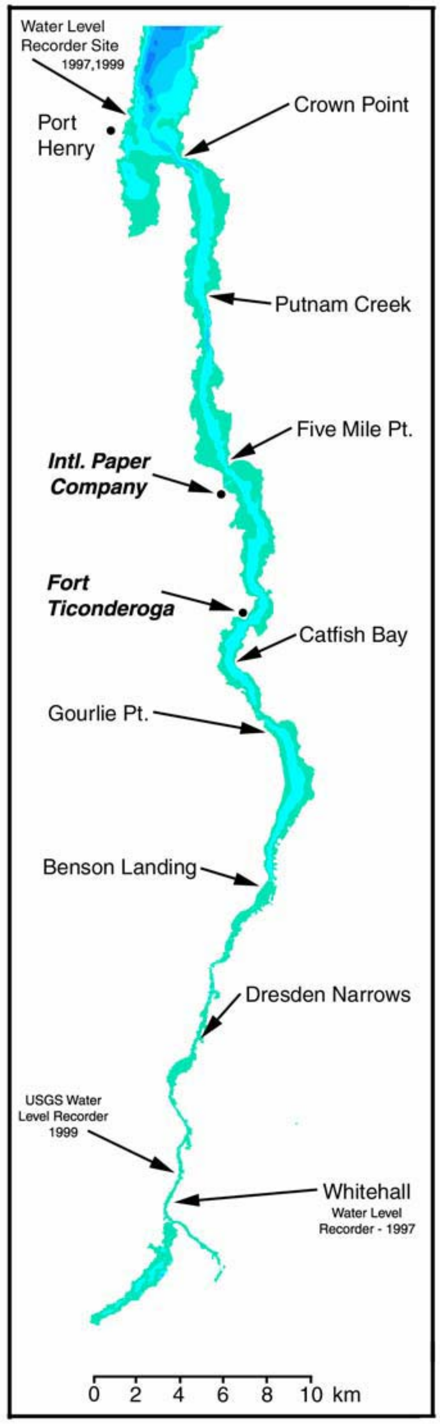

Figure 4. Location of instrumented sites during the summers of 1997, 1998, and 1999 within the South Lake.

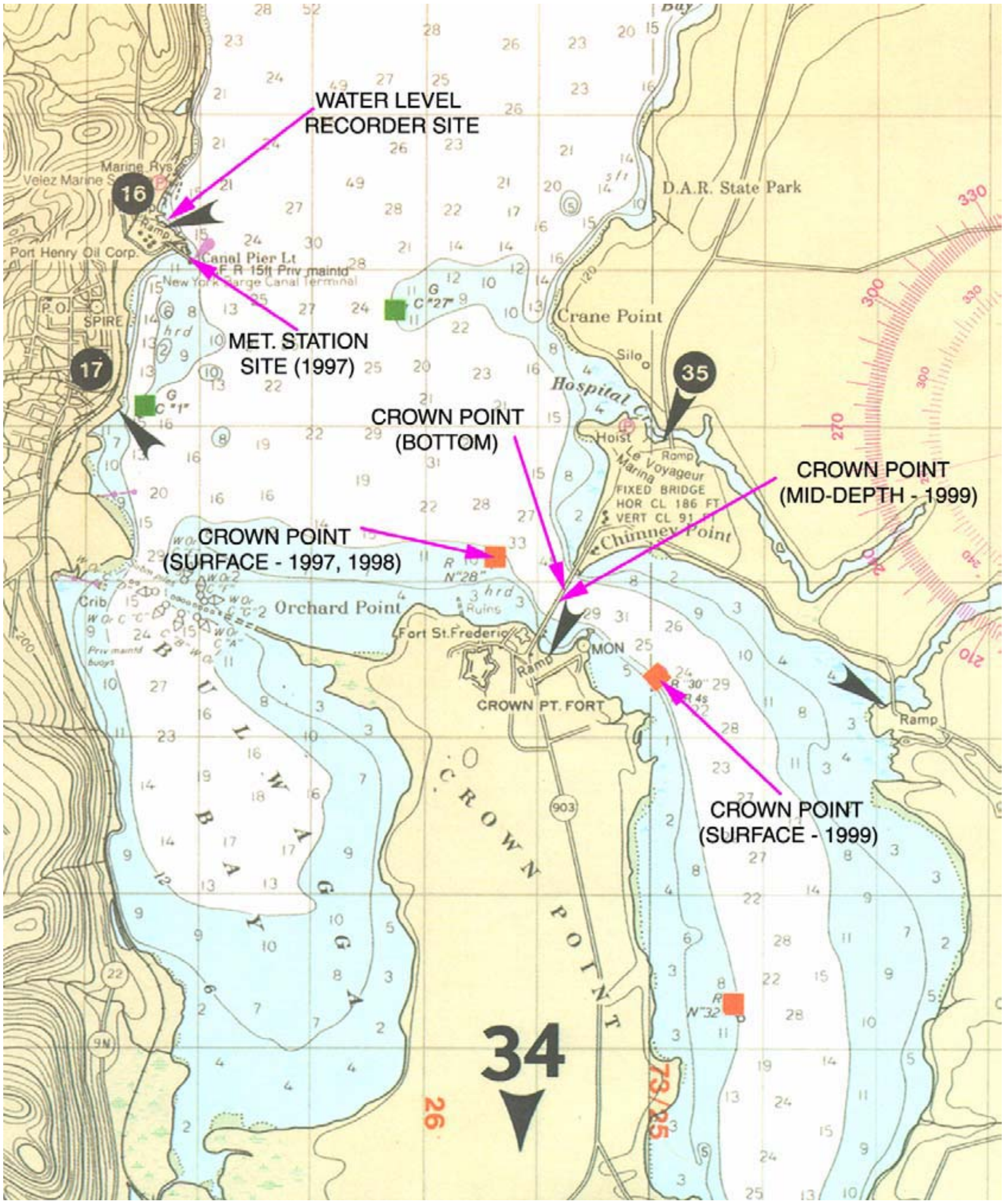

Figure 5. Location of the Crown Point bridge sites. Note that the deep site was in the center channel directly below the Crown Point bridge, while the shallow sites were those of navigational buoys directly north or south of the bridge itself. During 1999, an intermediate depth site was positioned on the western central pier of the bridge. During 1997, a side-looking ADCP was located near this mid-depth position.

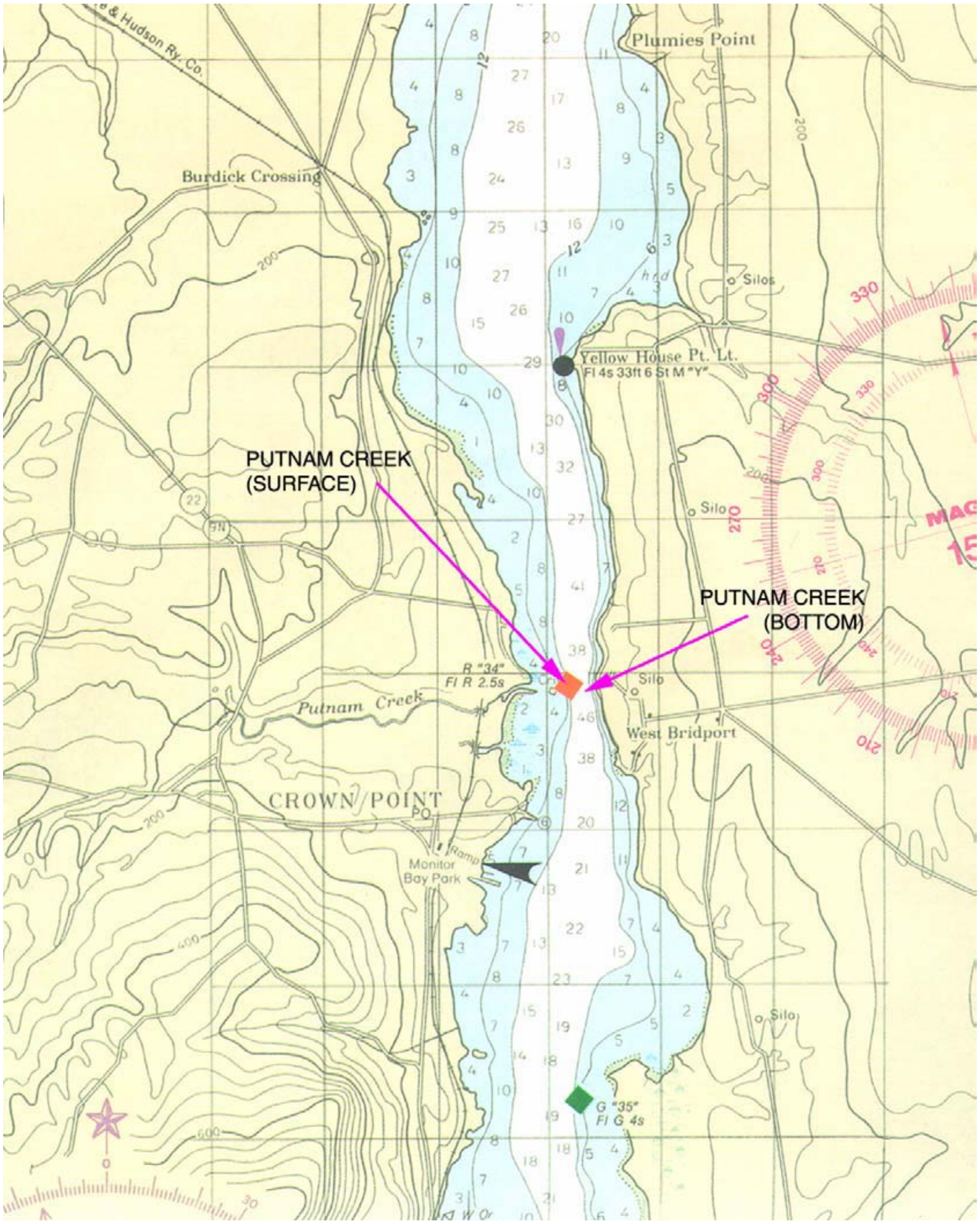

Figure 6. Location of the Putnam Creek site.

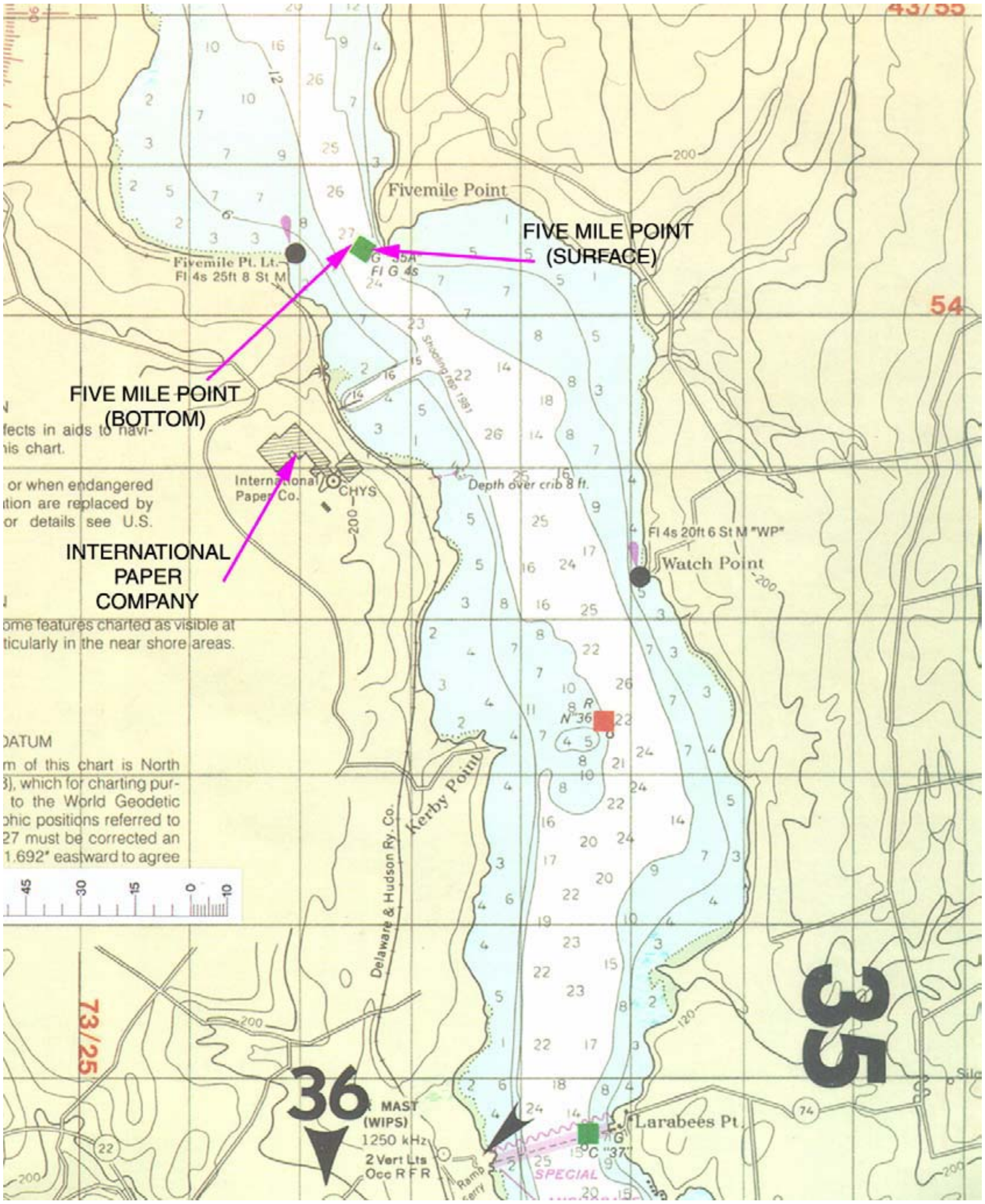

Figure 7. Location of the Five Mile Point site.

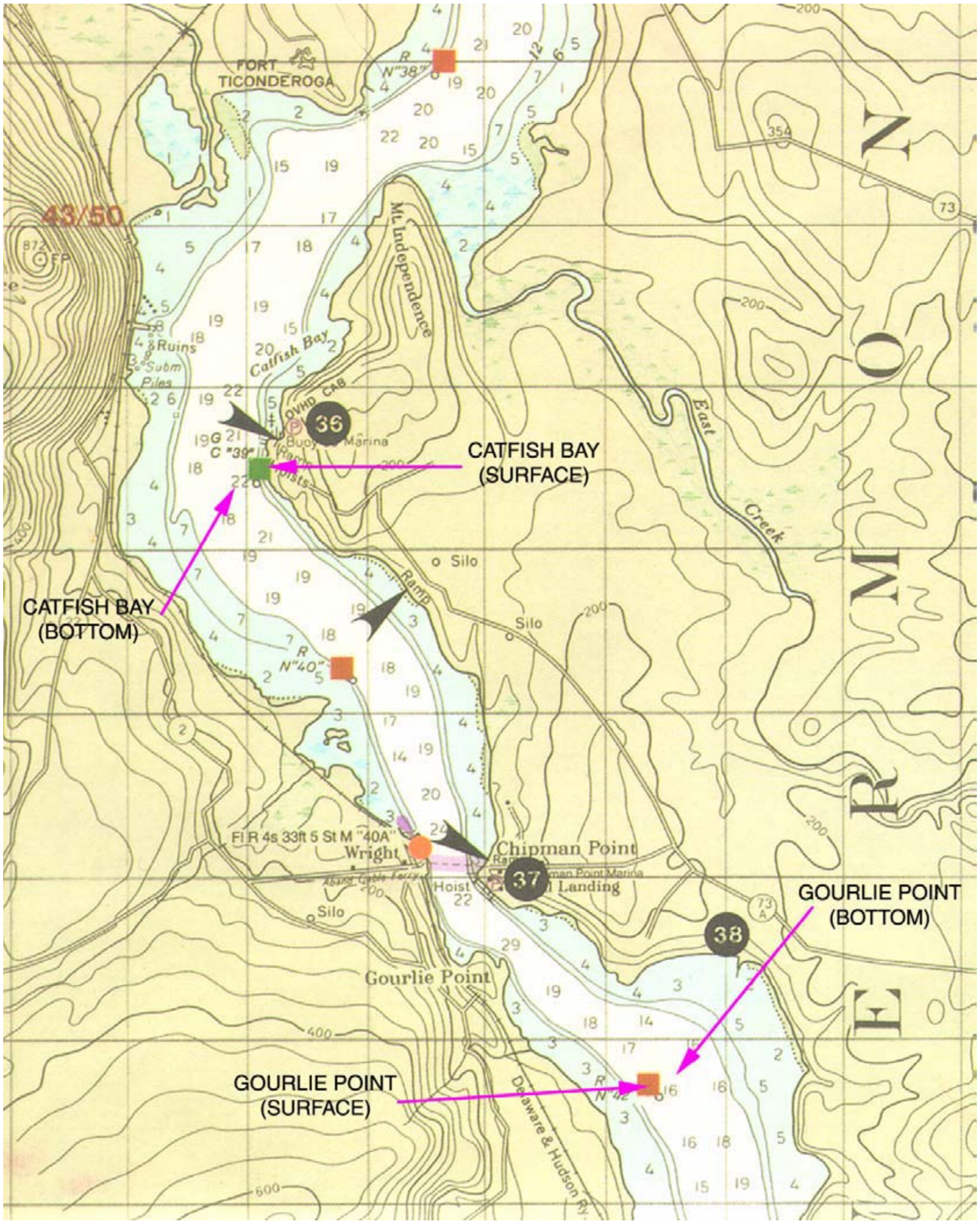

Figure 8. Location of the Catfish Bay and Gourlie Point sites.

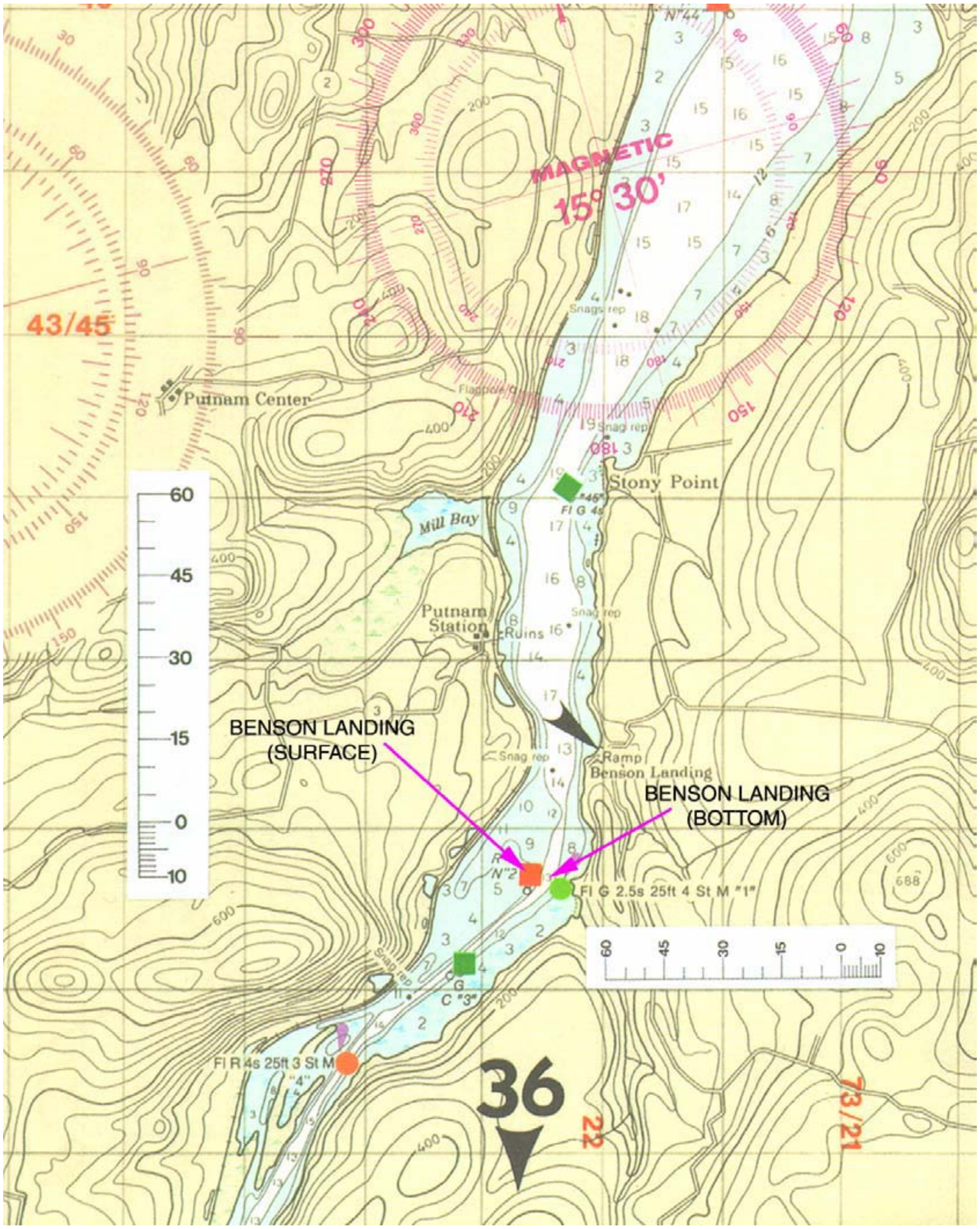

Figure 9. Location of the Benson Landing site.

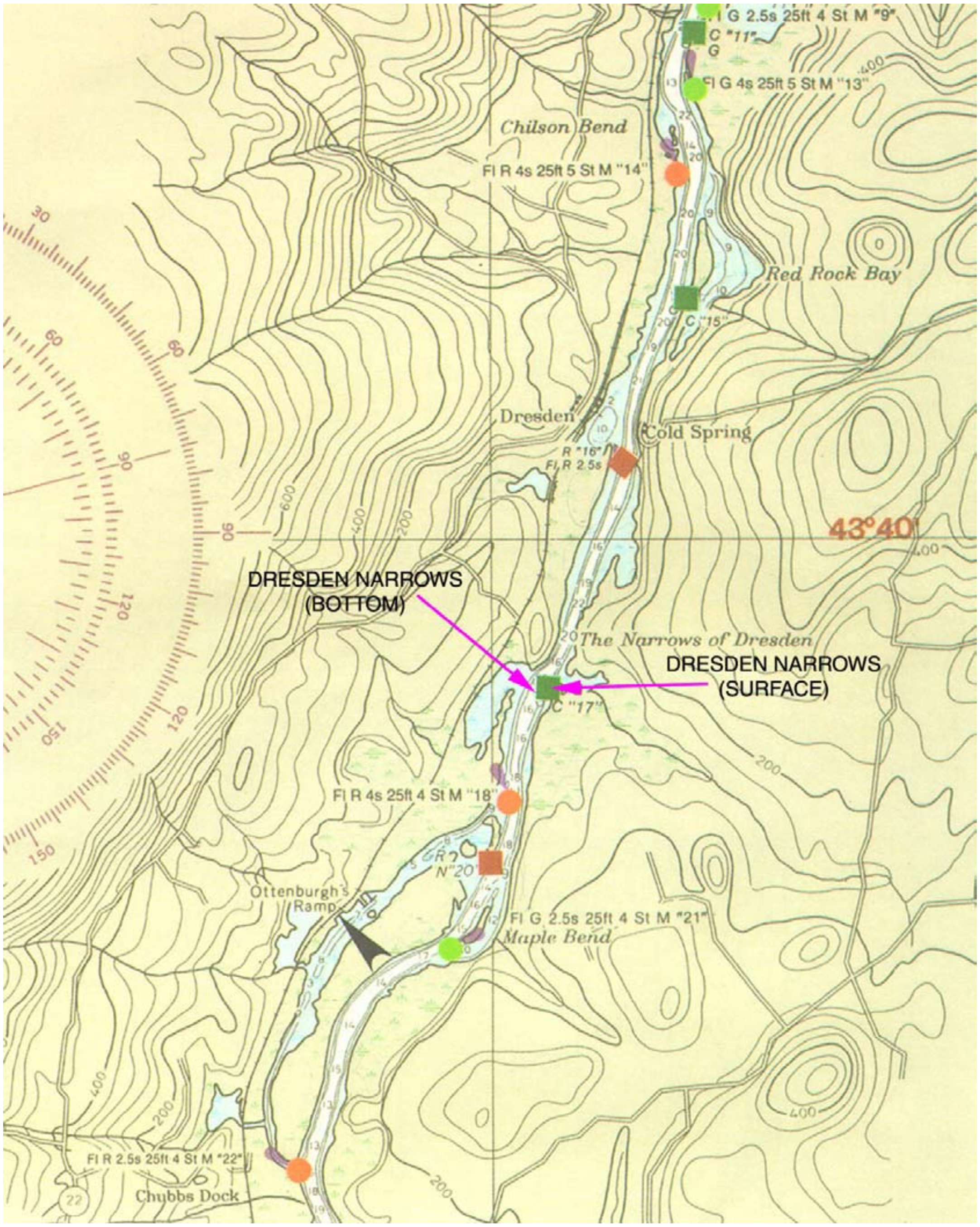

Figure 10. Location of the Dresden Narrows site.

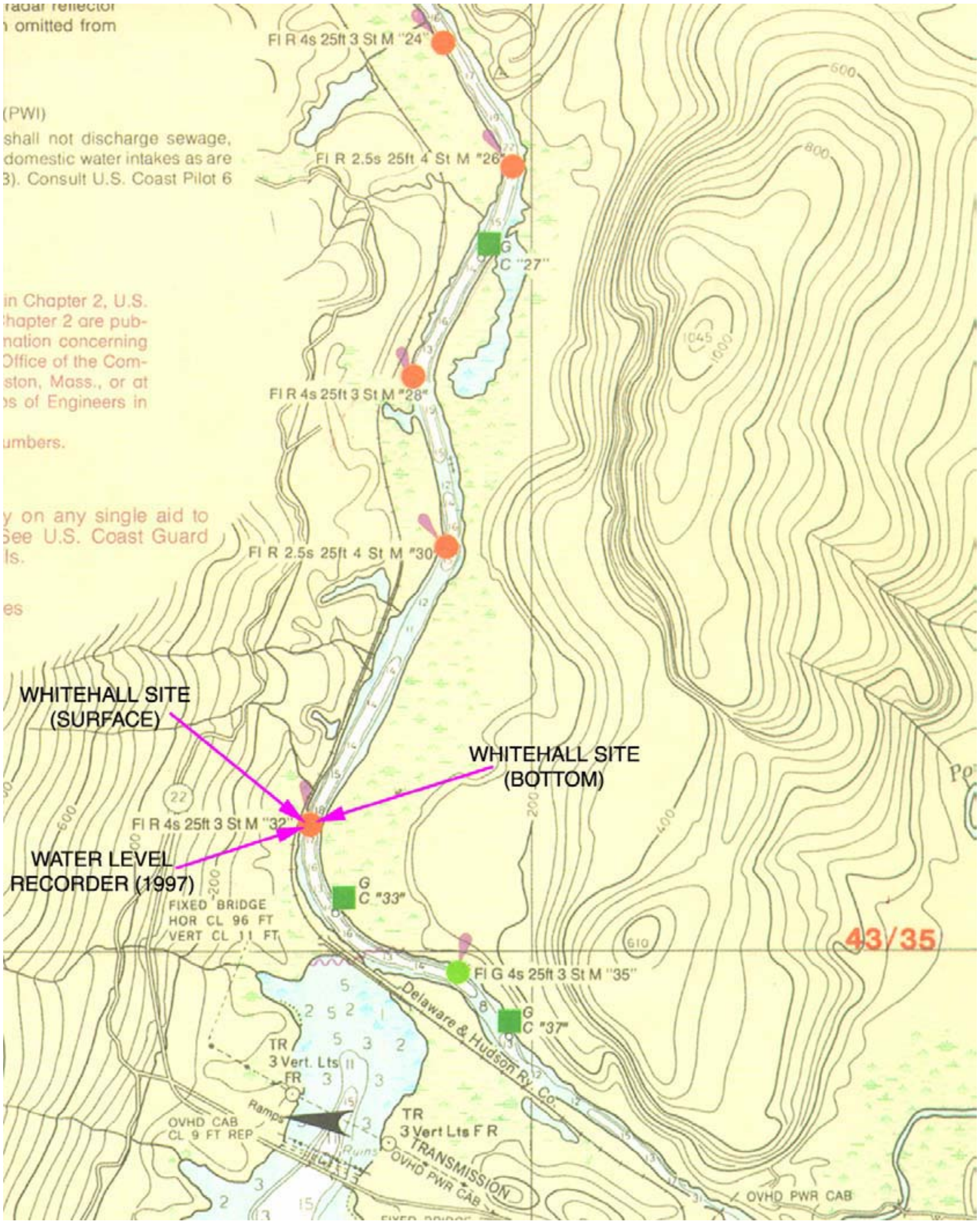

Figure 11. Location of the Whitehall site.

- Instrumentation -

Since it was important to monitor both the deep and surface water temperatures, a system was devised for both easy deployment and retrieval in near-zero visibility under water conditions. This system consisted of two separate components; the navigational aid itself and a separate anchor pad with standoff. For each navigational aid used, a temperature sensor was secured to the uppermost chain-link below the surface buoy. Depending on the type of buoy present, the depth of the temperature sensor could range from 0.9 to 1.8 m. The depth gauge of the SCUBA diver who installed them often documented the depth at which the sensors were placed.

In order to monitor the deep temperatures of the main channel above the sediment water interface, a standoff anchor pad system was fabricated. The system was composed of a 12 in. high stainless steel frame (to which the temperature sensor was attached) and a tractor wheel weight (forming its base). The total weight of the system (approximately 85 pounds in air; 65 pounds in water) prohibited easy movement of the temperature sensor. In specific cases, two tractor wheel weights were utilized to provide greater immobility where potential anchor-drag situations were a higher probability.

Once the surface temperature sensor was installed, a small diameter stainless steel wire rope was looped over the navigational aid and permitted to sink to the bottom thereby wrapping itself around the anchor pad. The other end of the wire rope was securely attached to the standoff. The boat was utilized to stretch the ground line into the deepest part of the center channel and deploy the standoff system through the use of a rope. The depth of the sensor was recorded as the measured length of the rope or the depth obtained from a NYDEC supplied fish finder.

In low-visibility underwater conditions, a SCUBA diver could locate the ground line by following the navigational aid's chain down to the bottom. The diver would then cut the ground line and then bring it to the surface. Once the diver was back on board the boat, two people would be used to haul in a single-weight standoff system. Where a double-weight system was used, three people were required.

The temperature sensors used for this program were internally recording Seamon Minis manufactured by Hugrun. Sampling accuracy is 0.1 $^{\circ}$C with measurement precision of 0.01 $^{\circ}$C. Longterm stability of these sensors suggests calibration every 5-8 years or during battery replacement at the factory (which ever is shorter). The sensors are totally programmable as to sampling rate from a few seconds to that of weeks. Data collected in 1997 and 1998 program were taken every 30 minutes; however, the sampling rate was increased to every 10 minutes in 1999 in order to capture higher frequency components.

During 1997, two water level recorders were installed by NYDEC in an effort to gain an initial understanding of lake level fluctuations at the northern and southern ends of the South Lake. The first water level recorder was installed at a boat landing facility at Stevens Point (Port Henry; see Figure 5). The second water level recorder was installed on the navigational pier at the Whitehall site (see Figure 11). The data collected from these two sites are shown in Appendix 4. An effort was made in 1998 to have the USGS install satellite-linked water level recorders within the South Lake. Due to prior commitments of time and money, the USGS was not able to install the Whitehall sensor until September 14th, after two-thirds of the 1998 field program had been completed. The Port Henry water level recorder was, however, operational for the entire year of 1998. Both of these sites remained operational until June 2000.

In 1997, a meteorological station was installed in Port Henry in an effort to gain more detailed information on localized wind forcing for the South Lake. Unfortunately, the meteorological station did not function properly and, as result, no data were collected during the year. During the 1998 field season, the International Paper Co. (IPC) permitted NYDEC and USGS to use one of their towers for a meteorological station (wind speed and direction only). It was not until January 9th, 1999 that the IPC met station became operational. For completeness of this report, it should also be mentioned that as of June 2000, support for the South Lake water level recorders as well as the meteorological station at IPC have been terminated due to lack of available funds. Is expected that these particular stations will be removed before September of 2000.

Due to the lack of meteorological observations in the South Lake prior to January 9, 1999, data from the Burlington International Airport (BIA) and Cholchester Reef (CR) were utilized in the analysis of thermal and water level data for 1997 and 1998. Both BIA and CR are both located near the central portion of the Main Lake on its eastern perimeter. BIA is located several miles inland of the city or Burlington while CR is located above the water surface at the USCG Cholchester Reef site. Of these two sites, BIA possessed the most consistent data and is routinely used in all three years. During 1998, CR had 14 days of non-recorded information during two data gaps. This increased to roughly 30 days during 1999 field season. IPC data possessed only 2 data gaps in 1999 that comprise the total of 10 days. As a consequence, CR was not utilized for any 1999 analyses although of the data are provided in Appendix 5c.

Because of the lack of South Lake meteorological and water level information during the 1998 field season, an additional year's funding was provided for the summer of 1999 so that all parameters (including water temperature) could be monitored simultaneously. This report provides as detailed an analysis as possible for each of the years 1997 to 1999 given the lack of many critical observations within the South Lake during 1997 and 1998.

In 1997, 1998, and 1999, water velocity observations could not be obtained due to the amount of money required for rental of equipment or direct purchase, not to mention a guarantee of replacement if lost. In 1997, however, the Crown Point Bridge became a testing site for a new side-looking ADCP made by RD Instruments of California. Due to its rather unique shape compared to that of the more rounded acoustical heads of the ADCPs, this instrument was named the ‘doghouse’ (Figure 12). The unit was attached to the corrugated-steel piling structure of the western central peer at a depth of 21 feet (at the same location of the 1999 mid-depth temperature sensor; see Figure 5). Figure 13 shows the doghouse on the day of the deployment (11 Sept.) facing directly across channel towards the eastern central pier of the bridge. During the installation process, care was given to it being perfectly level as well as the direction at which it was pointing. The period of observation extended until the 24th of Sept. 1997. The purpose of this instrument was to monitor velocity and echo intensity across the channel at this one specific depth. Correlations with other measurements taken at the Crown Point Bridge will be provided in more detail later on in this report.

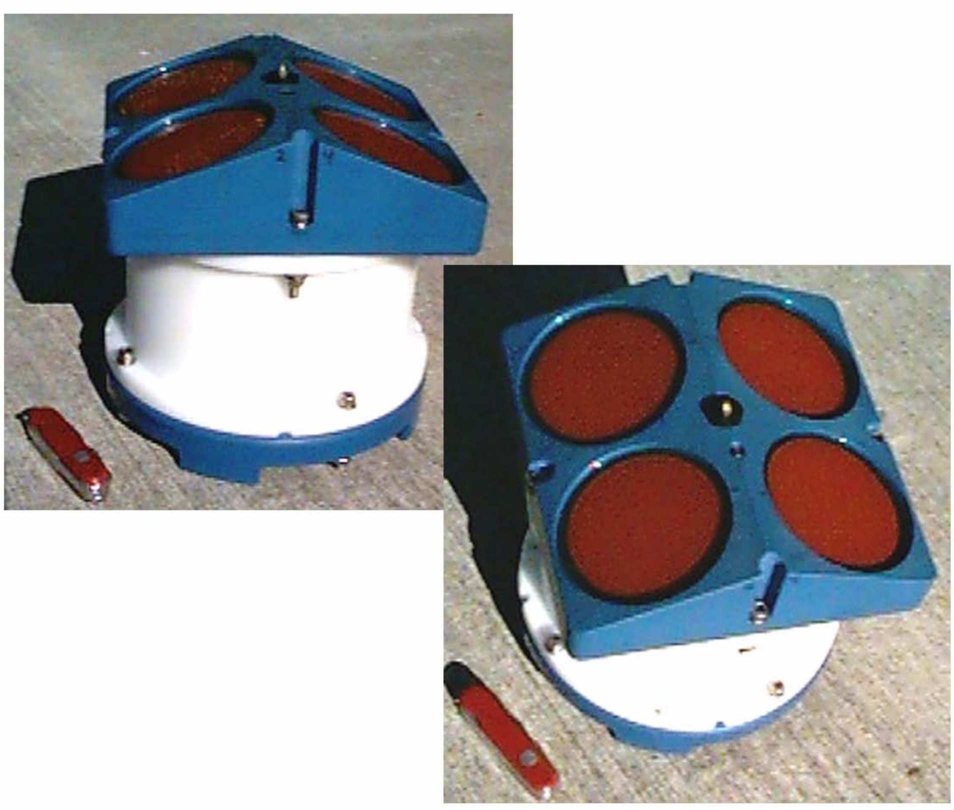

Figure 12. Prototype instrument called the "doghouse" for side-looking ADCP measurements. This instrument was created by RDI and tested at the Crown Point Bridge in September of 1997.

- Observations -

General Information

During each of the field seasons, the data collection window extended from mid-June to mid-October. Due to funding and scheduling issues, each year comprised a slightly different window of time, yet still overlapping. In 1997, data were collected from August 1 (day 213) to October 28 (day 302). In 1998, data were collected from July 9 (day 190) to October 15 (day 288). In 1999, they were collected from June 10 (day 161) to October 2 (day 275). For analysis purposes, the Gregorian calendar is often converted into a sequential Julian day system (relative to the beginning of that year). Since 1997, 1998, or 1999 are not leap years, Table 1 can provide a simple cross-reference between Gregorian and Julian dates.

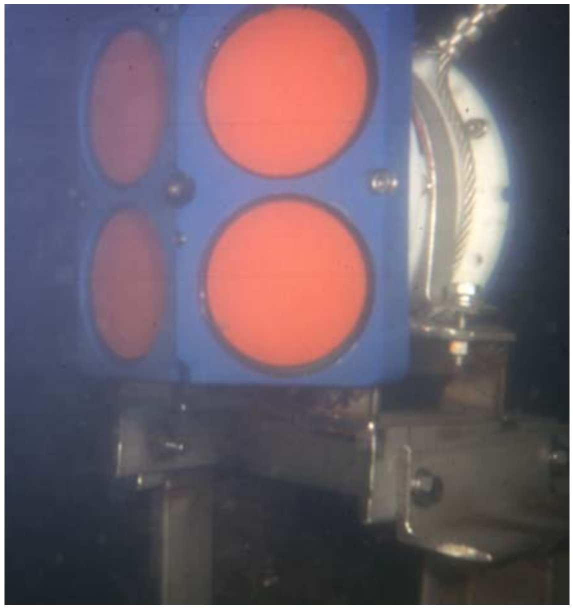

Figure 13. The “doghouse” mounted and secured to the underwater piling of the Crown Point Bridge.

Table 1. Gregorian and Julian day cross-reference list for the years 1997, 1998, and 1999.

Month	Day	Julian Day
Jan.	1	1
Feb.	1	32
Mar.	1	60
Apr.	1	91
May	1	121
June	1	152
July	1	182
Aug.	1	213
Sep.	1	244
Oct.	1	274
Nov.	1	305
Dec.	1	335

- Meteorological Data -

Appendix 5a, b, and c provide meteorological observations taken at BIA, CR, and IPC, respectively. As can be noticed in these records, there were several time periods where data were not collected or various sensors malfunctioned. The plots for each year are broken down into two forms: wind speed and direction, and component wind speed (north-south and east-west). North and east are represented by positive values, whereas south and west are represented by negative values. With respect to wind direction and component speeds, it should be noted that these plots are referenced in terms of oceanographic observations (i.e., directions to which the wind blows) rather than meteorological ones for easier comparison with water level, current meter and thermal observations.

Table 2 provides general statistics for all three years at the three meteorological sites. Comparisons of CR and BIA during 1997 and 1998 show that CR is consistently higher in velocity by a factor of two to three. Wind direction, however, appears to be similar when looking at the average, but slightly different (~10 degrees) when comparing medians.

Table 2. Statistical information from meteorological stations within the Champlain Valley during 1997, 1998, and 1999 for BIA (Burlington International Airport), CR (Cholchester Reef), and IPC (International Paper Company). Statistical fields are number of observations, median, average, standard deviation, variants, minimum, and maximum.

Year	Site	Parameter	Num.	Med.	Avg.	StdDev	Var.	Min.	Max.
1997	BIA	Air Temp.	2065	15.5	14.4	6.9	46.9	-4.4	32.2
		Speed	1776	3.1	3.6	1.8	3.3	1.3	10.7
		Direction	1776	60.7	36.7	-	-	4.6	355.8
		Speed (E-W)	1776	0.3	0.3	1.9	3.9	-7.2	6.4
		Speed (N-S)	1776	0.2	0.5	3.5	12.0	-9.1	10.3
1997	CR	Air Temp.	1879	16.9	15.5	5.7	31.9	0.2	29.7
		Speed	1879	5.1	5.5	2.8	8.0	0.2	13.6
		Direction	1879	47.5	45.3			0.0	360.0
		Speed (E-W)	1879	1.2	1.1	2.9	8.6	-13.0	13.6
		Speed (N-S)	1879	1.1	1.1	5.2	26.6	-12.1	12.2
1998	BIA	Air Temp.	2329	18.2	17.9	5.6	31.0	-0.74	31.2
		Speed	2329	2.7	3.0	2.0	4.1	0.01	10.4
		Direction	2329	69.4	45.3			0.1	360.0
		Speed (E-W)	2329	0.5	0.6	1.5	2.2	-4.3	9.8
		Speed (N-S)	2329	0.2	0.6	3.2	10.1	-6.6	9.7
1998	CR	Air Temp.	2023	19.2	18.4	4.4	19.7	4.8	27.9
		Speed	2023	5.2	5.4	3.0	8.9	0.2	16.5
		Direction	2023	41.2	42.7			0.1	359.7
		Speed (E-W)	2023	1.8	1.8	2.5	6.0	-5.9	13.6
		Speed (N-S)	2023	2.1	1.9	5.0	25.3	-10.0	16.3
1999	BIA	Air Temp.	3145	19.6	19.0	7.0	48.5	-3.3	35.2
		Speed	3145	2.7	3.1	2.2	5.0	0.0	13.6
		Direction	3145	37.8	37.4			0.0	360.0
		Speed (E-W)	3145	0.3	0.6	1.6	2.4	-4.2	6.7
		Speed (N-S)	3145	0.3	0.7	3.4	11.4	-13.1	10.1
1999	IPC	Air Temp.	2905	N/A	N/A	N/A	N/A	N/A	N/A
		Speed	2905	2.6	2.9	1.9	3.8	0.0	15.2
		Direction	2905	5.2	17.9			0.0	360.0
		Speed (E-W)	2905	0.1	0.3	1.4	2.1	-3.2	7.3
		Speed (N-S)	2905	1.2	0.8	3.1	9.6	-15.2	8.5

It has often been noticed that BIA/CR wind data, while defining characteristics of the central Main Lake, do not adequately represent observations at the far reaches of Lake Champlain. The implementation of the IPC meteorological station represents the first opportunity to directly compare between winds observed in the South Lake and those at BIA. Using the median and average values found in Table 2, BIA shows a significant variation in wind direction (30 and 20 degrees, respectively) greater than that reported by IPC. This is also confirmed in Figure 14 (a & b) through the use of polar histograms for wind direction as well as standard histograms for speed (c & d). Additionally, there were many instances where component wind speeds reported at IPC were opposite to that observed that BIA. Although the speed histograms appear to be similar between BIA and IPC, it is important to note that these differences, particularly at lower velocities, may become significant with respect to future numerical simulations of the South Lake. In recent numerical simulations of Lake Champlain by ASA, it was evident that the lack of credible low-wind speeds and directions failed to produce observed circulation patterns (Dr. Dan Mendelson, personal communication).

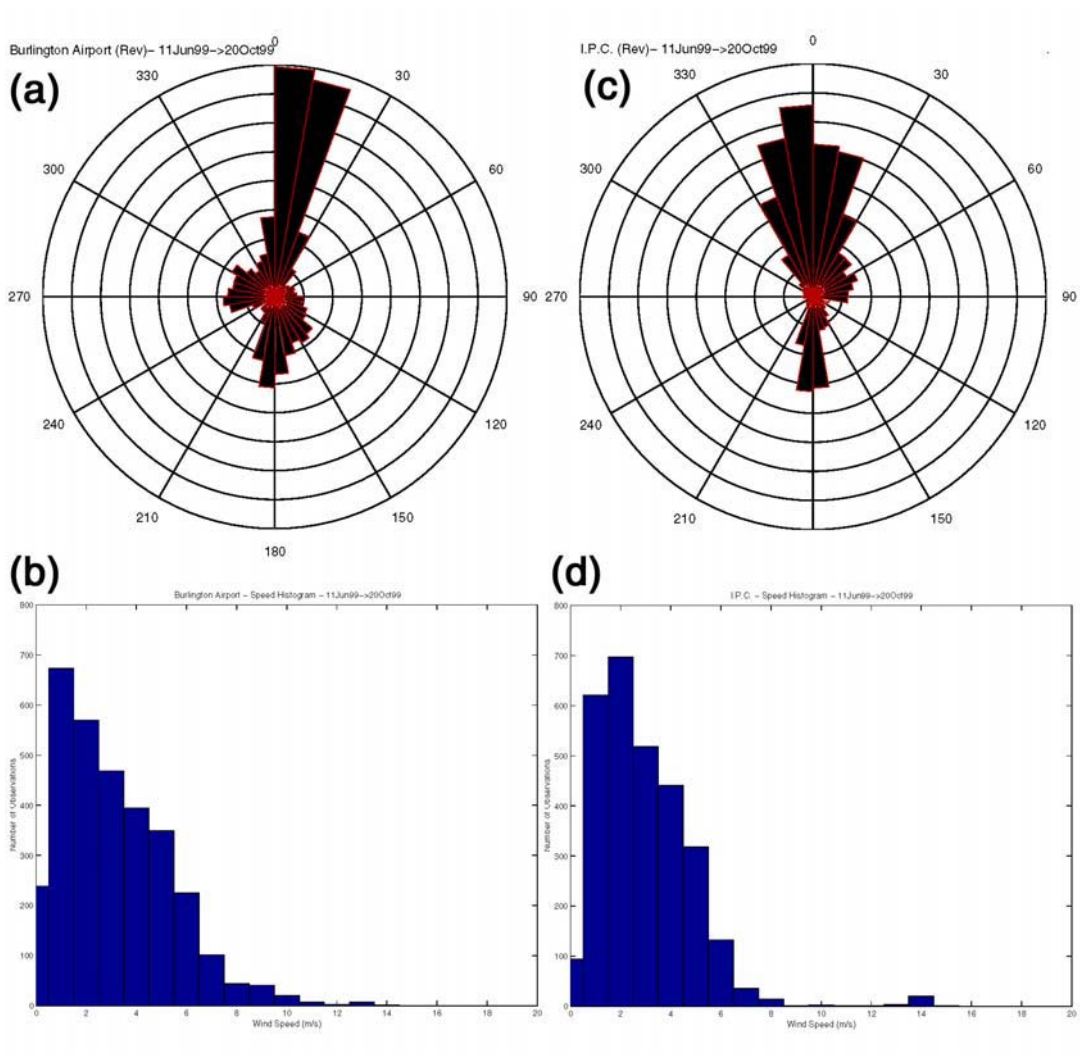

Figure 14 provides visual comparison between the polar histograms of directional frequency as well as standard speed histograms.

Spectral analysis of the various components of wind speed as well as wind speed magnitude also showed consistent variations between BIA and IPC. Typically, BIA preceded most of the wind events at IPC by approximately 3 hours in the north-south component and as much as 8 hours in the east-west component. With respect to the magnitude of wind speed, spectral analysis indicated that for the major spectral components, IPC lagged behind BIA from 0.5 hours to 6.2 hours. Additionally, IPC data consistently provided better spectral comparisons with South Lake data than that of BIA (e.g., cross-spectral analysis utilizing BIA wind forcing often showed weak or no correlation with several measured parameters, however, IPC provided significant correlations). While the observed directional shift at IPC is most likely due to stronger topographic steering in the vicinity of the South Lake, it is important to restate that these variations in wind speed and direction should be considered significant when future numerical simulations of this region are attempted.

- Water Level Data -

Appendix 4 provides water level data for 1997, 1998, and 1999. As previously mentioned, 2 sites were maintained during most of this time. The first was located north of the Crown Point Bridge at the Stevens Point docking facility at Port Henry, while the second was located at the Whitehall site. This Whitehall site, properly referred to as U.S. Coast Guard navigational aid No. 32, is a solid pier structure. In 1997, the water level gauge itself was attached to a double-weight standoff pad along with the shallow temperature sensor. At Stevens Point, the water level recorder was attached to one of the metal bulkheads. Mr. Rob Burnham and Dr. Scott Quinn of the NYDEC installed both devices. Both sites measured water level relative to their own datum plane and therefore, must be considered relative observations. In 1998, the USGS took over responsibility for the water level stations at Stevens Point and the Whitehall site. In contrast to the 1997 observations, these particular sites were referenced to the standard lake level of 93 feet defined on all Lake Champlain NOAA charts. Unfortunately, it was not until the latter part of the 1998 field program that both sites were fully operational.

Visual comparison between the east-west and north-south wind velocities obtained at the CR meteorological station show a very strong correlation between north-south wind forcing and that of water level variations observed at both sites in 1997 (Figure 15). East-west wind forcing, as seen in Figure 16, does not show such a strong correlation nor, would one expect such a correlation over the narrower axis of this river-like environment.

As can be seen in the 1997 and 1999 water level data (when both sites were operational; Figures 15 and 17), higher amplitude lake-level oscillations are almost consistently observed at Whitehall and not at Port Henry. It is visually apparent that many of the higher frequency events observed at Whitehall can be seen to exist at Port Henry, but at amplitudes 2-5 times smaller. Two individual events at days 220 (lowering) and 226 (rising; Figure 18) show a consistent lag of approximately 3 hrs from Port Henry to Whitehall. This may suggest the presence of a traveling long-period wave from north to south and/or a simple natural response time for the South Lake. A simple calculation for the natural resonant period of the South Lake shows 5.7 hours using an average depth of 2.7 m and length of 53 km. Half of this natural resonant period (2.85 hours) would represent the one-way travel time from Port Henry to Whitehall. This agrees well with observations.

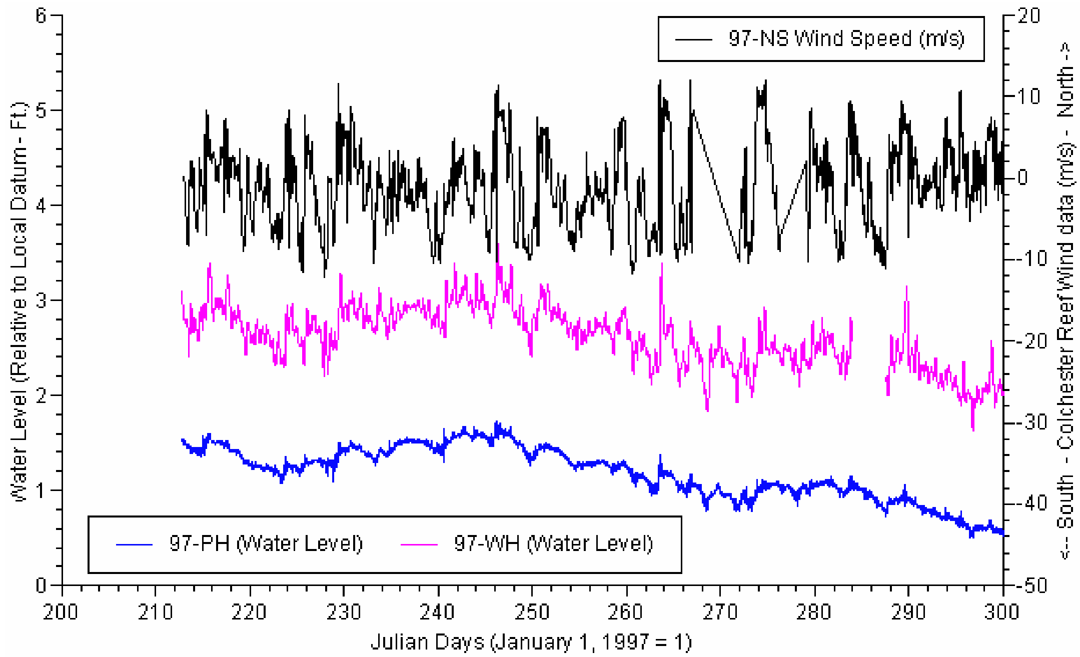

Figure 15. Water level data collected during 1997 at Port Henry and Whitehall shown with N/S wind velocity data from Colchester Reef. Note that straight lines fill data gaps.

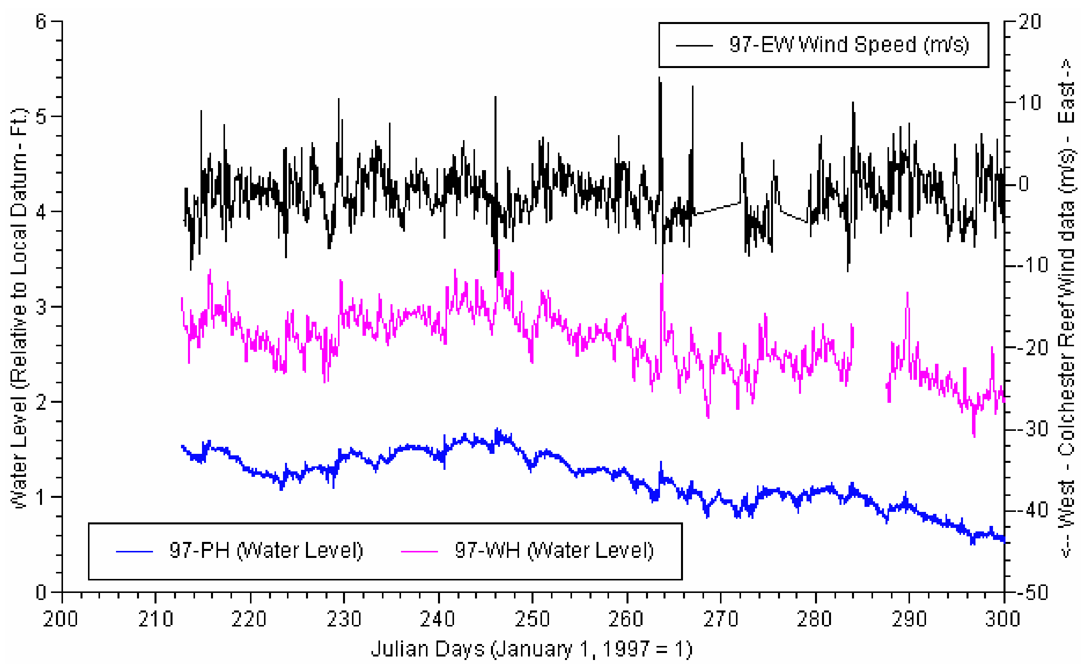

Figure 16. Water level data collected during 1997 at Port Henry and Whitehall shown with E/W wind velocity data from Colchester Reef. Note that straight lines fill data gaps.

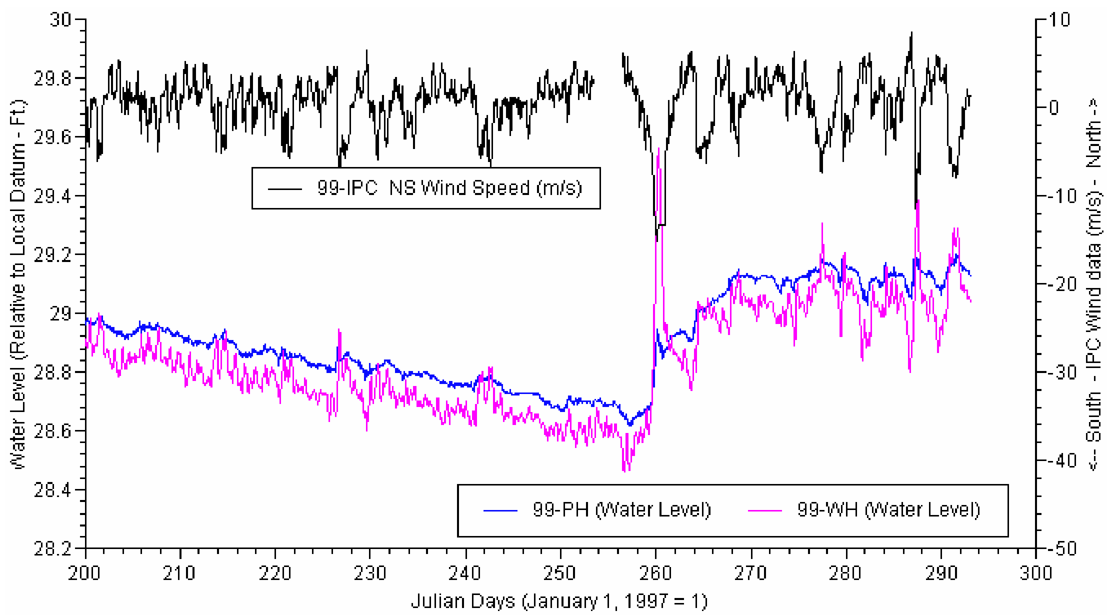

Figure 17. Water level data collected during 1999 at Port Henry and Whitehall shown with N/S wind velocity data from IPC.

The elevated water levels at Whitehall with respect to Port Henry also agree well with previous observations on Lake Champlain by Myer and Gruendling (1979). Although not well documented in the South Lake, Myer and Gruendling (1979) showed higher lake setups to be a function of narrowing and shoaling of the Main Lake moving northwards. The South Lake represents a similar environment except the narrowing and shoaling are more extreme when compared to the north end of lake. Hence, the South Lake appears to act as a magnifier for oscillations occurring in the southern portion of the Main Lake.

During extreme wind forcing events, this effect can be quite obvious. Cases in Point would be at days 226, 242, 260 and 287 (Figure 17). The largest of these was caused by hurricane Floyd as it moved through the Champlain Valley over the 16th and 17th of September, 1999. With maximum hourly averaged wind speeds of 13.6 and 15.2 meters per second at BIA and IPC, respectively, South Lake levels at Whitehall rose rapidly to heights of 0.97 meters above the preceding normal levels in a matter of 1.04 days. Due to the heavy rains associated with hurricane Floyd, water levels did not return back to their previous norm but rather 0.34 meters higher than the preceding normal levels. Over the course of the next several weeks, water levels consistently rose throughout the South Lake system. It should also be noted for completeness that the USGS water level recorders do not appear to have the same datum level in that Whitehall shows a lower lake level than Port Henry. If such a case were true, the long-term hydraulic head would force a southward flowing current throughout the entire South Lake (i.e., opposite from what it is). It is estimated that this error is approximately ~0.2 ft.

Spectral analysis on both water level recorders show a dominance of energy with periods greater than 1 day and not that of the South Lake's natural resonant period of approximately six hours. While spectral peaks will vary from season to season and year to year depending upon atmospheric forcing (Manley et al, 1999), several dominant periods (the top five spectral peaks) were observed in both the 1997 and 1999 data sets. These were 2.37-2.67, 1.78, and 1.52 days. 1.07 day was a strong spectral peak in 1997 but was eighth in 1999. Other spectral peaks outside of the most common ones previously defined were 5.33-7.11, 2.13, and 1.33 days. Since the natural resonant period of the South Lake is on the order of six hours, these previously defined dominant spectral peaks characterize external or atmospherically forced oscillations (Manley et al., 1999). Many of these spectral peaks are observed in the meteorological information, particularly those of 2.67-5.33, 1.78,1.52,and 1.02-1.07 days. Therefore, it appears that water levels within the South Lake were forced by longer period atmospheric events greater than 1 day.

Although it is possible that the South Lake does possess an internal natural resonant period, it has not appeared as an obvious signal in any of the thermal records obtained within this region. Given that the average depth of the thermocline is 10 m, the thermocline shore would have its maximum extent some 9 km to the South (Putnam Creek) of the Crown Point Bridge. Extension of the thermal properties of Lake Champlain (Manley et al., 1999) to this region would indicate that the fundamental period for such an internal standing wave to be approximately 1.7 days. While this appears to fit within the 1.52-1.78 day spectral peak band, it is unlikely that this internal seiche period is the cause of this widely observed spectral band. If it were the case, then only observations taken from Putnam Creek northwards would possess this period and not those stations to the south. In reality, this spectral band is widely observed throughout the South Lake as far down as Whitehall. Atmospheric winds would therefore represent the primary driving force for the dominant modes of oscillation found in the South Lake.

- Thermal Information -

Appendices 1, 2, and 3 possess all site-specific thermal data for the years 1997, 1998, and 1999, respectively. Two-letter nemonic codes have been given to each of the site locations: Port Henry (PH), Crown Point (CP), Putnam Creek (PC), Five Mile Point (FM), Catfish Bay (CB), Gourlie Point (GP), Benson Landing (BL), Dresden Narrows (DN), and Whitehall (WH). The legend of each plot defines the colors used, the specific year, site location, and depth. Only one temperature sensor failed during the three years of observations. This was due to a flooding of the deep temperature sensor at Putnam Creek in 1999.

To better visualize the correlation between the various sites, several additional plotting methods were utilized. These appear in Appendices 6 through 17, and represent groupings of deep and shallow sensors within the entire South Lake. For example, all near-surface temperature data for all sites within the South Lake during 1997 are plotted on a single diagram. Within that same appendix, 20-day expanded plots are also provided for the same information. A subsequent appendix provides the same year's information, but for bottom thermal information. Two additional appendices are provided for that same year. Both follow the same basic format as previously described, however, the thermal traces for each site have been offset from each other by 2 ^{o}C. This permits better relative comparison between the various sites for any given year.

Surface Temperatures

Virtually all surface temperatures recorded in the South Lake from years 1997 to 1999 have strongly coherent temperatures and variability. As might be expected, air temperature variations are directly correlated with the surface observations, albeit with some associated phase lag. Figures 18, 19, and 20 provide an overview of all shallow surface temperatures taken within the South Lake over the years 1997, 1998, and 1999, respectively.

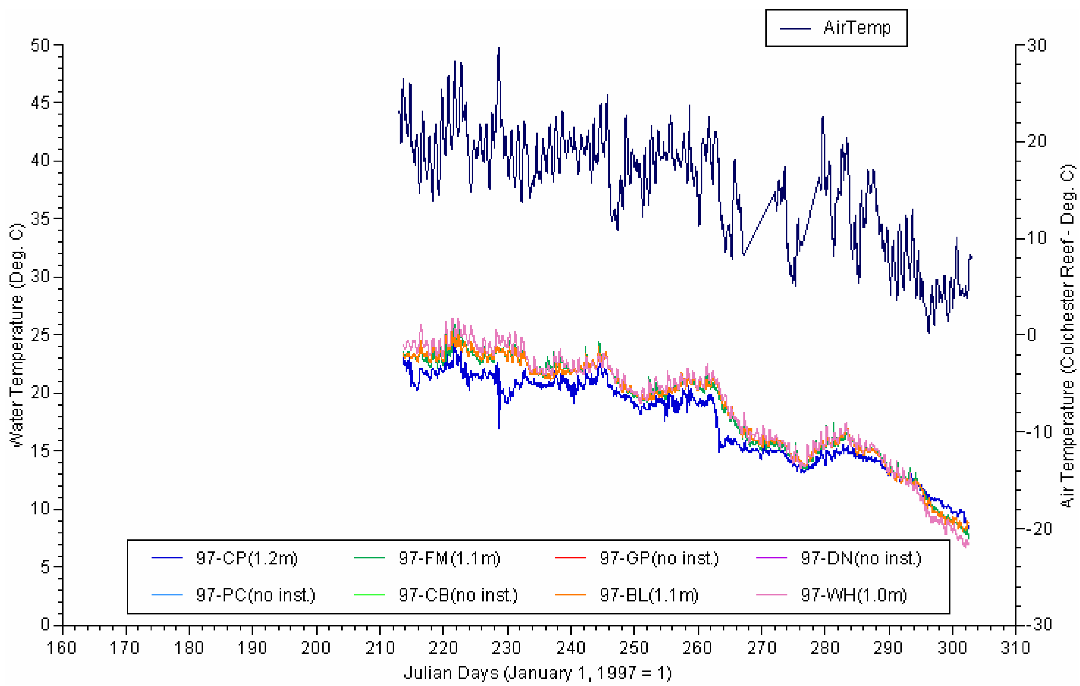

Figure 18. Surface temperature observations at all sites during 1997. Air temperature from the Colchester Reef meteorological station is also included. Note that in this year, temperature observations were not made at Putnam Creek, Catfish Bay, Gourlie Pt., or Dresden Narrows. Note that straight lines fill data gaps.

Cross-spectral analysis between BIA air temperature and the top temperature sensors at Crown Point and Whitehall clearly show the dominance of diurnal forcing. Other strong cross-spectral peaks appear at 5.33, 1.33, and 0.85-0.89 days. Cross correlation with these top temperatures and north-south directed winds at BIA showed very weak correlations. Using IPC wind data however, the dominant significant peak appeared at 1.12 days. This can be explained by the fact that wind often possesses a diurnal component that is driven by the relative difference in heating of the land and water surfaces. As one moves to the deeper temperature sensors, cross spectral analysis shows weaker and weaker correlations with increasing depth. A case in point would be that of the Crown Point bottom temperature sensor, which shows no cross-spectral correlations with temperature.

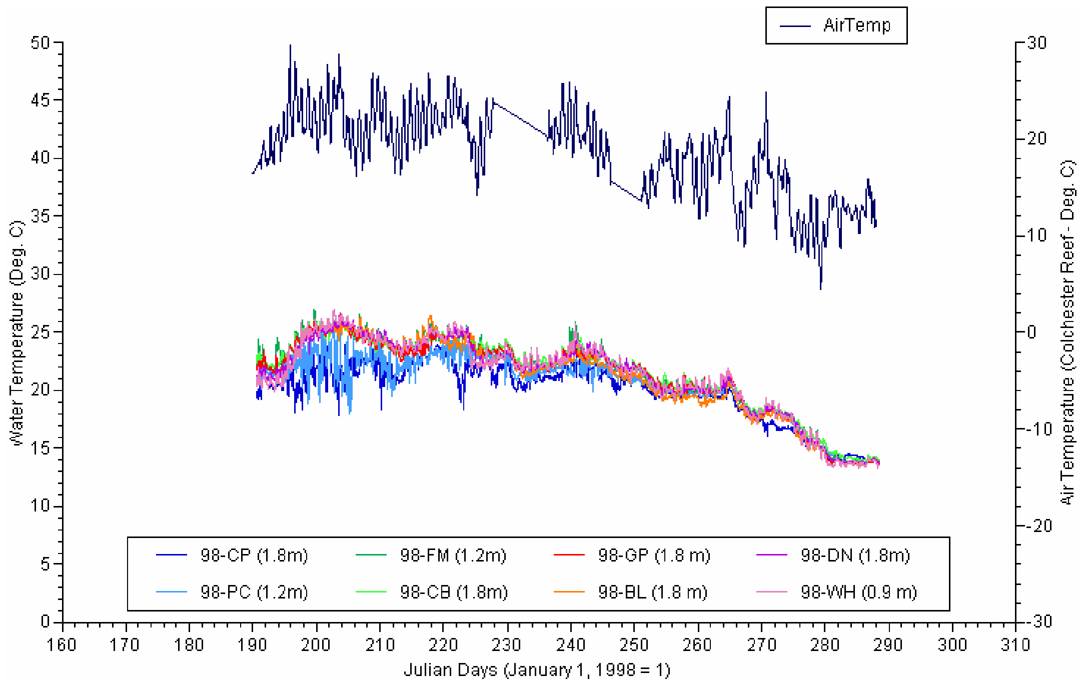

Figure 19. Surface temperature observations at all sites during 1998. Air Temperature is from CR. Note that straight lines fill data gaps.

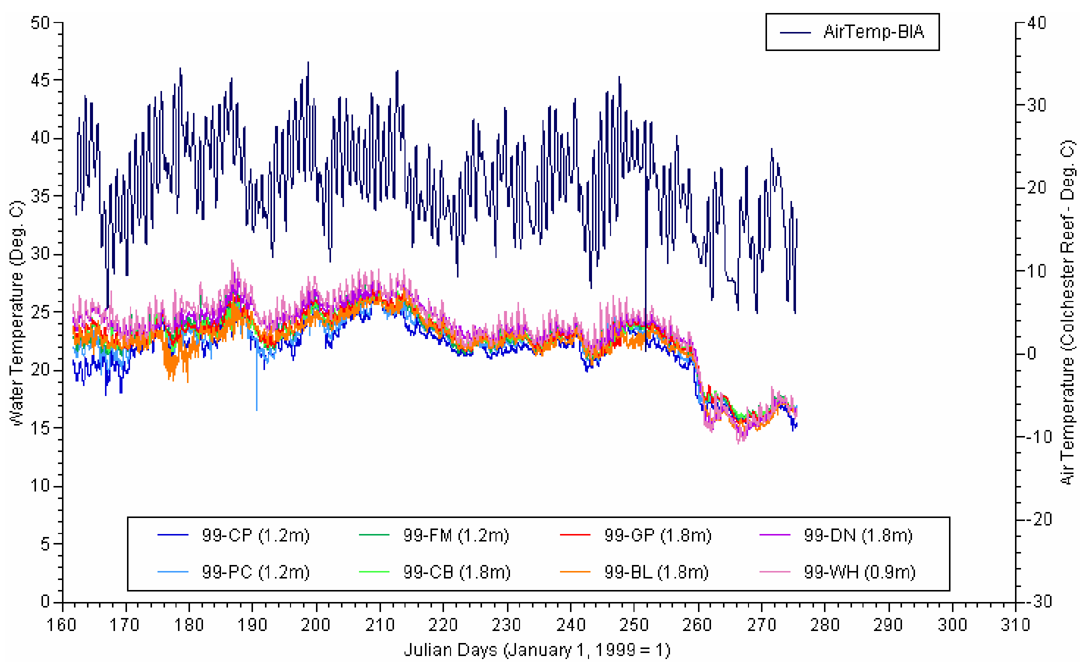

Figure 20. Surface temperature observations at all sites during 1999. Air Temperature is from CR.

When compiling the auto spectral analyses over three years at the eight various sites along the South Lake, a compilation of the five highest peaks for each analysis created a list of 25 dominant periods. These ranged from 0.59 to 5.33 days. In order to assimilate these into a meaningful set of observations that reflect the larger South Lake domain, a summary table was created to reflect the total number of times any given particular period was observed divided by the number of the number of spectral analyses. In this particular case, a total of 20 spectral analyses were completed for the top temperature sensors over three years of observations. Table 3 defines these results in terms of percent occurrence for given period. As expected from previous observations, the diurnal spectral peak was found within the first five dominant spectral peaks of each individual analysis. Clearly, it represents the most dominant mode of oscillation within the South Lake. Following the diurnal period with occurrence percentages of 40 and 35 percent are the groups of 3.52,1.52 and 5.33,1.33, and 0.50 days, respectively. These are less robust signals but are nonetheless significant modes that are atmospherically driven.

Table 3. Dominance of auto-spectral peaks over the entire South Lake for near surface temperature sensors. All eight observational sites were included in the analysis.

Period (days)	number of occurrences	maximum number of potential occurrences	occurrence percentage
1.02	20	20	100
3.52 1.52	8	20	40
5.33 1.33 0.50	7	20	35

All years show similar diurnal to seasonal trends. Although they are recorded during slightly different time periods within the year, the general trend of decreasing temperatures through time is apparent. On most occasions, surface temperatures at all sites become very similar and highly coherent with respect to variability past Julian day 220. Prior to this time, there tends to be more variability as well as a wider range of temperatures being observed within the South Lake. Since surface temperatures were all taken within a relatively narrow vertical range of 0.6 m (i.e., from 1.2 m to 1.8 m; Whitehall being the exception at 0.9 meters), there is some indication that these variations in temperature may reflect an environmental segmentation of the South Lake. This segmentation could be produced in a wide variety of ways, some of which would be due to natural restrictions, varying bottom topography, and/or the presence of river input. The proximity to the South Main Lake also plays an important role in the variability of surface temperatures as can be seen in Crown Point and Putnam Creek variability. Temporal scales of synoptic atmospheric motion can also be observed in these records by longer-term oscillations (5-10 days) of lake surface temperature.

It should also be noted that in 1998, the surface temperature sensor at Benson Landing (serial number 213) was inconsistent with the suite of temperature sensors at the site (i.e., the bottom senor at 3.7 m depth) as well as immediately to the north (Gourlie Point) and south (Dresden Narrows). When compared to the surface temperatures at Gourlie Point and Benson Landing, it appeared as though there was a consistent offset of 7 ^{o}C between days 202 – 276. The preceding record from day 161.75 – 201.95 was anomalously high even after the offset had been applied and was therefore removed. Both high and low frequency events within the corrected record match the nearby surface sensors at Gourlie Point and Dresden Narrows very well. As a result, the Benson Landing surface sensor was included in the data for event timing purposes only. One can see the close mapping of this sensor with the other surface sensors in Figure 21.

Diurnal variations of the surface water are apparent in Figure 21, which is an expanded view of the 1998 data taken at the 8 sites along South Lake. Atmospheric temperature variations are also shown on the plot and are coherent with those observed at virtually all other sites. Outside of the proximal sites to the Main Lake (Five Mile Point, Putnam Creek, and Crown Point), the strongest response to atmospheric forcing can be observed at Whitehall. This can be attributed to be very close proximity of the temperature sensor to the surface (0.9 m). All other surface temperature sensors, when compared to Whitehall, displayed smaller amplitudes, which were directly related to their increased depth away from the surface.

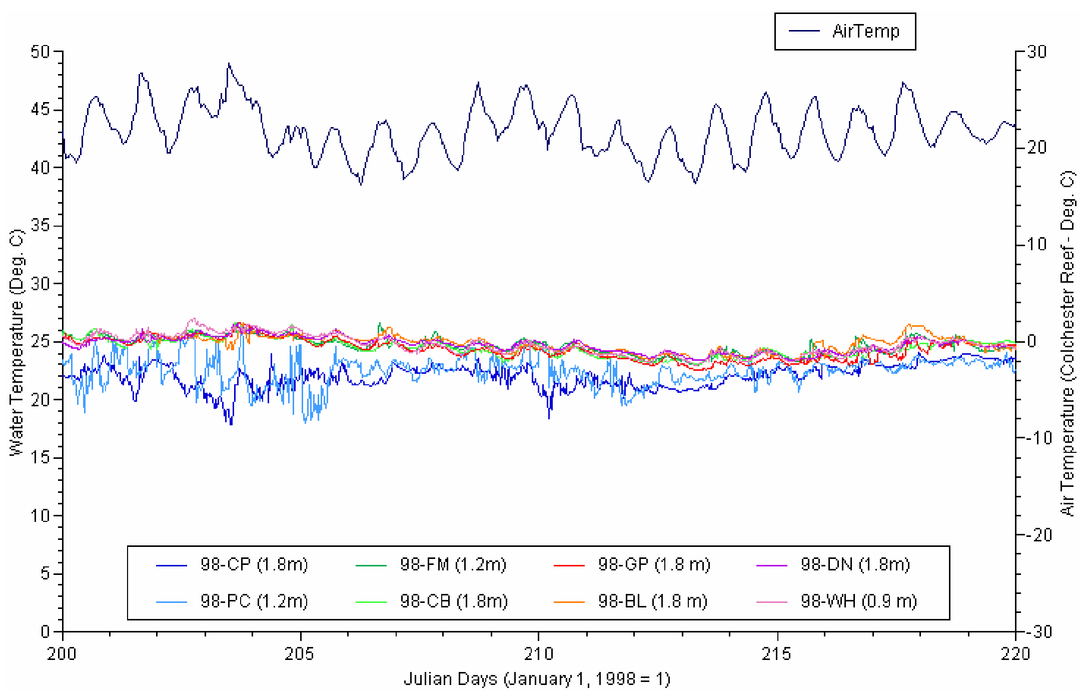

Figure 21. Surface temperature observations at all sites during 1998, however, expanded over a 20-day period ranging from mid to late August. Air temperature from the Cholchester Reef meteorological station is included.

Deep Temperatures

Deep temperatures observed in the South Lake for all years have a much wider range of variability, both temporally and thermally. Figures 22, 23, and 24 provide information at all sites during the years 1997, 1998, and 1999, respectively. In 1997, the first indication of strong thermal differences along the lake bottom became apparent. This was evidenced by the large variation seen between Crown Point and Benson Landing. A more detailed comparison of the 1997 Benson Landing and Crown Point thermal data can be seen in Figures 25 and 26, respectively. At Benson Landing, both the deep and surface temperatures mimic each other to a high degree. Diurnal variability is much more evident in the surface temperature sensor; however, it does also appear in the deeper data. Crown Point thermal data possesses a higher degree of thermal variability, both in the surface and deep layers prior to Julian day 265. After that, seasonal cooling reduces the temperature difference between the two sensors and enhanced similarity becomes apparent. The very strong thermal differences observed between the upper and lower sensors defines two very distinct thermal regimes; a warm epilimnion and a colder metalimnion or hypolimnion. It is more probable that the deep sensor, on average, is within the metalimnion.

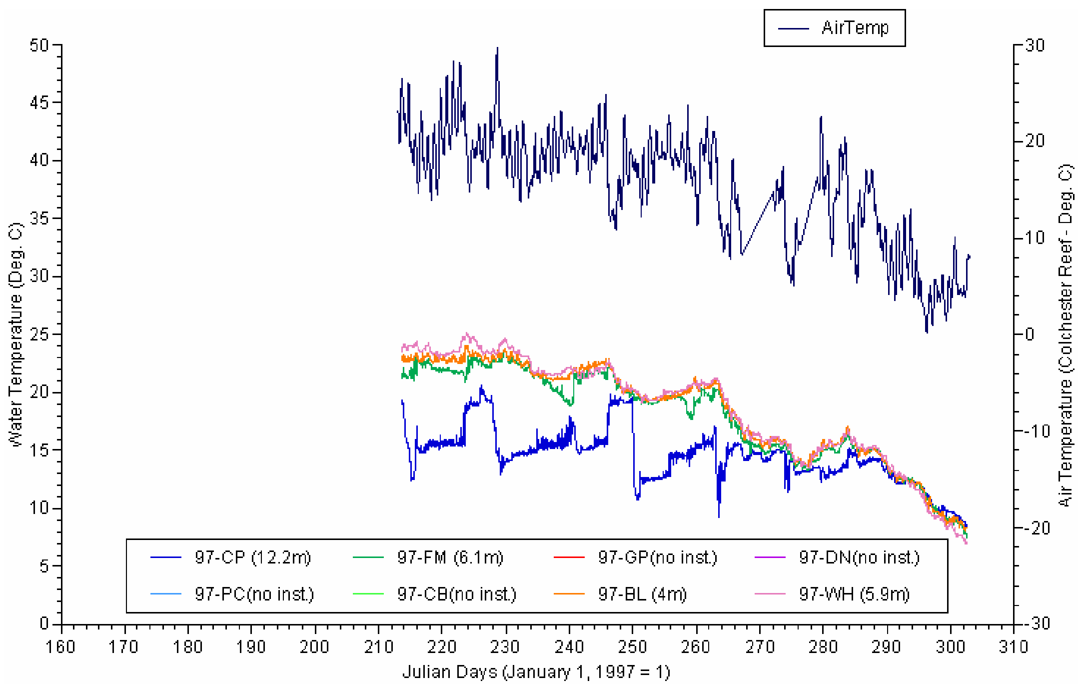

Figure 22. 1997 deep temperatures at all sites. Air temperature from Cholchester Reef is provided. Note that in this year, temperature observations were not made at Putnam Creek, Catfish Bay, Gourlie Point, and Dresden Narrows. Note that straight lines fill data gaps.

Dominant modes of preferred oscillation were also calculated for the bottom temperature sensors within the South Lake. Table 4 provides these results. Since the South Lake is predominantly shallow, the dominance of the 1.02 day spectral peak is understandable. Periods of 1.78, 2.67, 1.33, 1.19 and 0.5 days have similarly been observed in the auto-spectra of Colchester Reef, BIA, or IPC. The 4.27 day signal is strongest north of Catfish Bay and may reflect the oscillatory motion of the uninodal internal seiche within the Main Lake. Additionally, the 2.67 and 1.94 day modes may also reflect other dominant modes of the Main Lake's internal seiche at periods of 2.7 and 1.8 days (Manley et al., 1999).

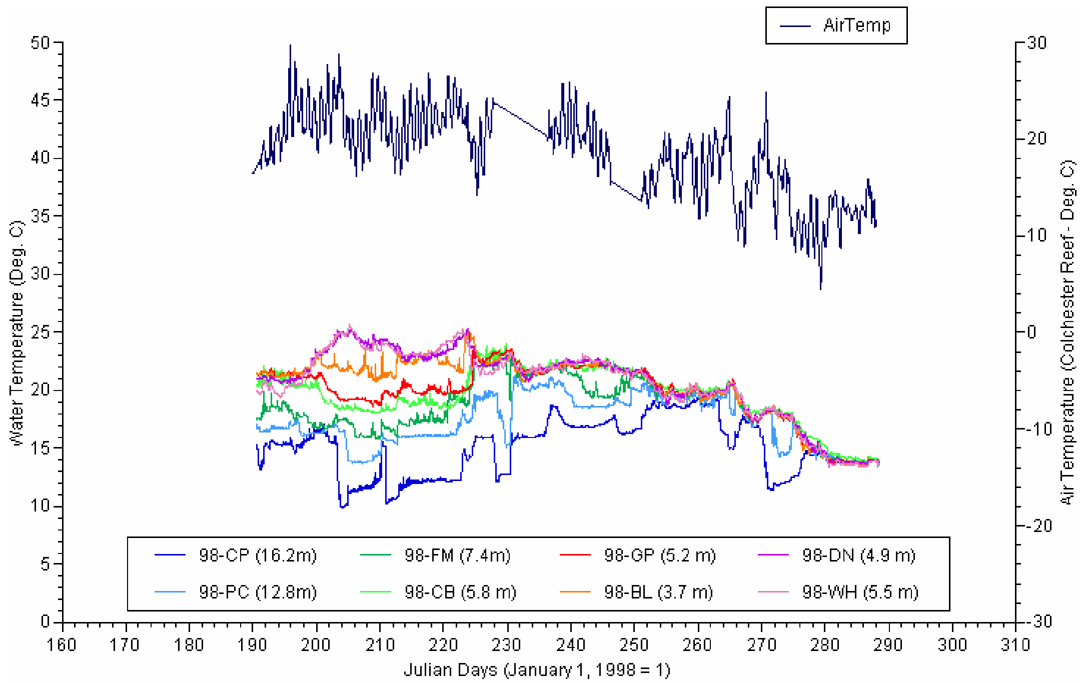

Figure 23. Deep temperature observations at all sites during 1998. Air temperature from the Cholchester Reef meteorological station is also shown. Note that straight lines fill data gaps.

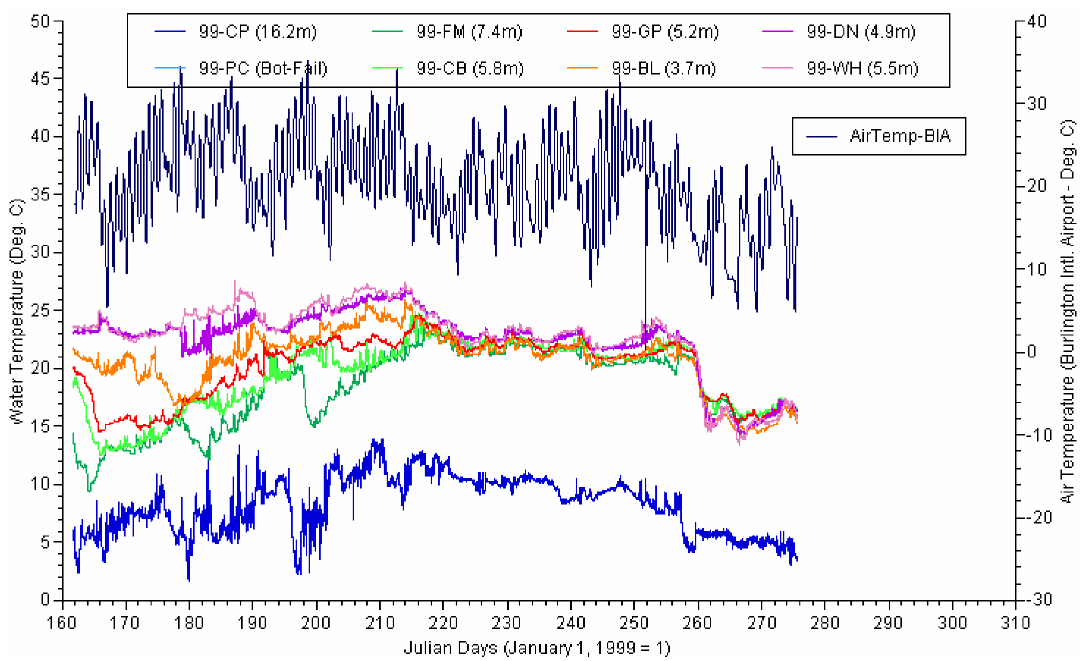

Figure 24. Deep temperature observations at all sites during 1999. Air temperature from the Burlington International Airport meteorological station is also shown.

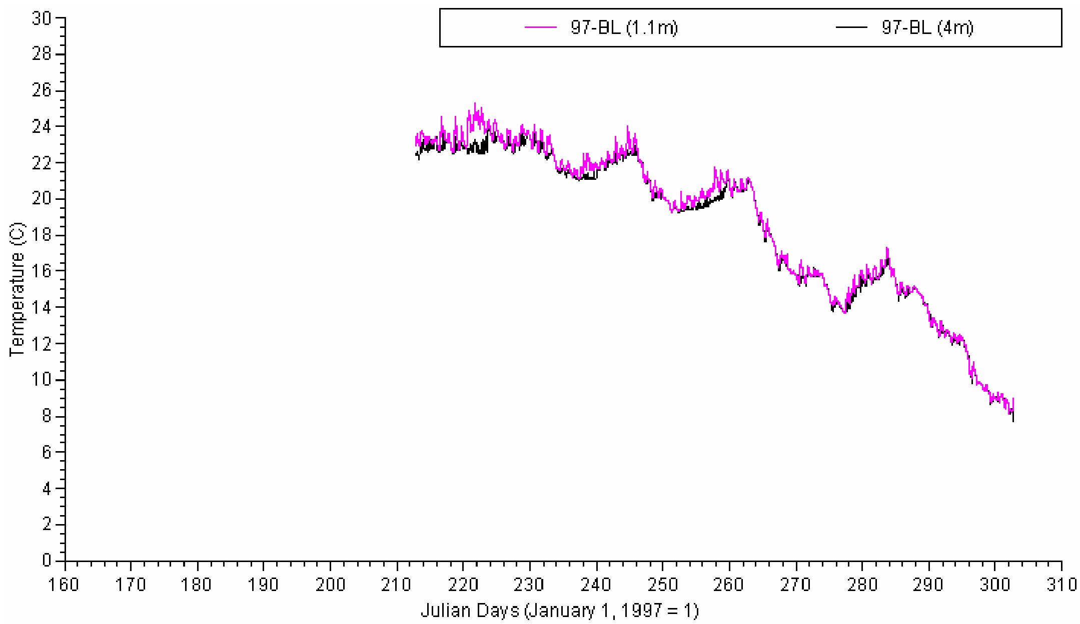

Figure 25. Benson Landing thermal data for 1997. Surface and deep temperatures were taken at 1.1 m and 4 m, respectively.

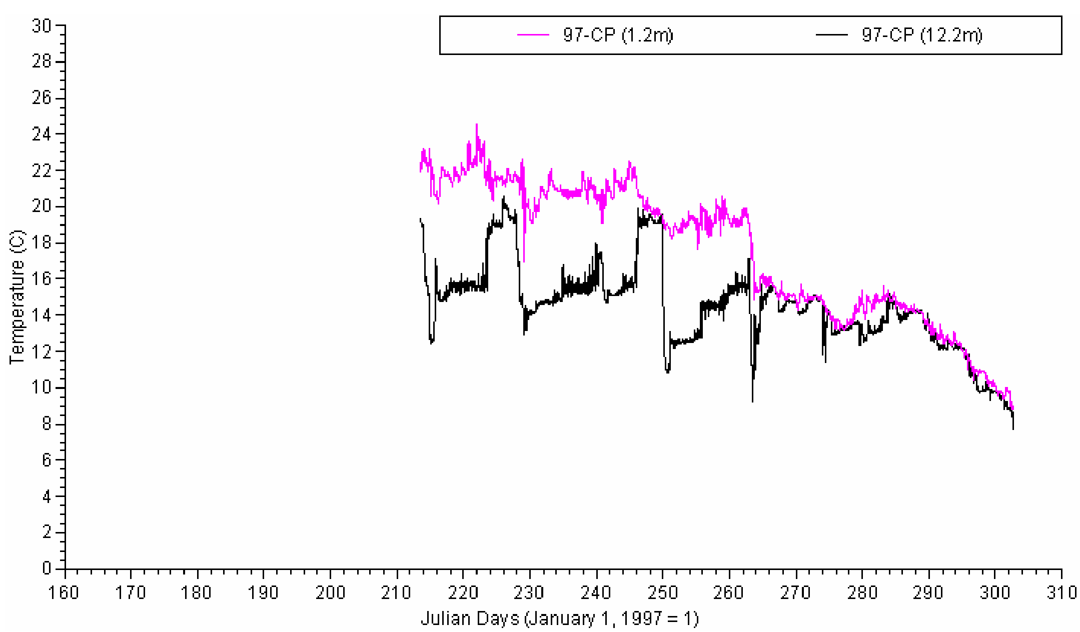

Figure 26. Crown Point thermal data for 1997. Surface data was taken at 1.2 m while deep data was observed at 12.2 m.

The last remaining spectral peak of 1.42 days requires some additional elaboration. Unlike the longer period signal of 4.27 days, which appears only in the northern portion of the South Lake, the 1.42 day peak appears throughout the entire South Lake. While this 1.42 day period has been observed within the Main Lake by Manley et al. (1999), it is strongest during wintertime and most likely associated with an atmospheric spectral peak at 1.5 days. Closer inspection of the spectral records shows that 80% of 1.42 day peaks occurred during 1998, and it was only during that year that the 1.42 day spectral peak occurred at any of the meteorological stations, specifically CR. The remaining 20% of observations with 1.42 days may be forced with the more commonly observed 1.52 day spectral peak frequently observed at the meteorological stations. In brief, the South Lake appears to have a preferred response at 1.42 days, but may not be frequently observed due to the fact that atmospheric forcing may not possess that specific component on an annual basis.

Table 4. Dominance of auto-spectral peaks over the entire South Lake for Bottom temperature sensors. All eight observational sites are included.

Period (days)	number of occurrences	maximum number of potential occurrences	occurrence percentage
1.02	15	19	79
1.42	10	19	53
1.94 1.78	7	19	37
2.67 1.19	6	19	32
4.27	5	19	26
1.33 0.50	4	19	21

What is most striking are the large thermal oscillations observed in the deep center channel at the Crown Point bridge. These thermal oscillations represent bi-modal variability (i.e., increases as well as decreases in temperature). Invariably, rapid decreasing temperatures immediately followed a warming event. These rapid drops in temperature, when viewed with expanded time scales (see Figure 29), have unique thermal signatures in the shape of a fishhook. An example of one such feature can be found at day 203 in Figure 23. Due to their unique signatures, these particular features, which include the preceding thermal rise in temperature, will be referred to as "thermal hooks". The rapid thermal drop in temperatures within these thermal hooks can approach 10 ^{0}C in just a few hours (e.g., Figure 29 at day 250). Four thermal hook events with expanded scales are provided in Figures 27, 28, 29, and 30. The textbook case of such a thermal event is that found from day 250-251 at Crown Point and shown in Figure 29. In this case, a large thermal increase of 4 ^{o}C was observed at 12.2 m (days 246-250) prior to the 9 ^{o}C drop in temperature (day 250-250.8) associated with the leading edge of the hook. The trailing edge of the event (day 250.8-251.2) warms by approximately 2 ^{o}C and subsequently maintains that temperature for a lengthy period of time afterwards (days 251.2-256). When looking at years 1997, 1998, and 1999, there appears to be, on average, 6 thermal hooks per observational period. Specifically, 6 moderate to strong events were observed in 1997, 8 events were observed in 1998, and 4 events were observed and 1999.

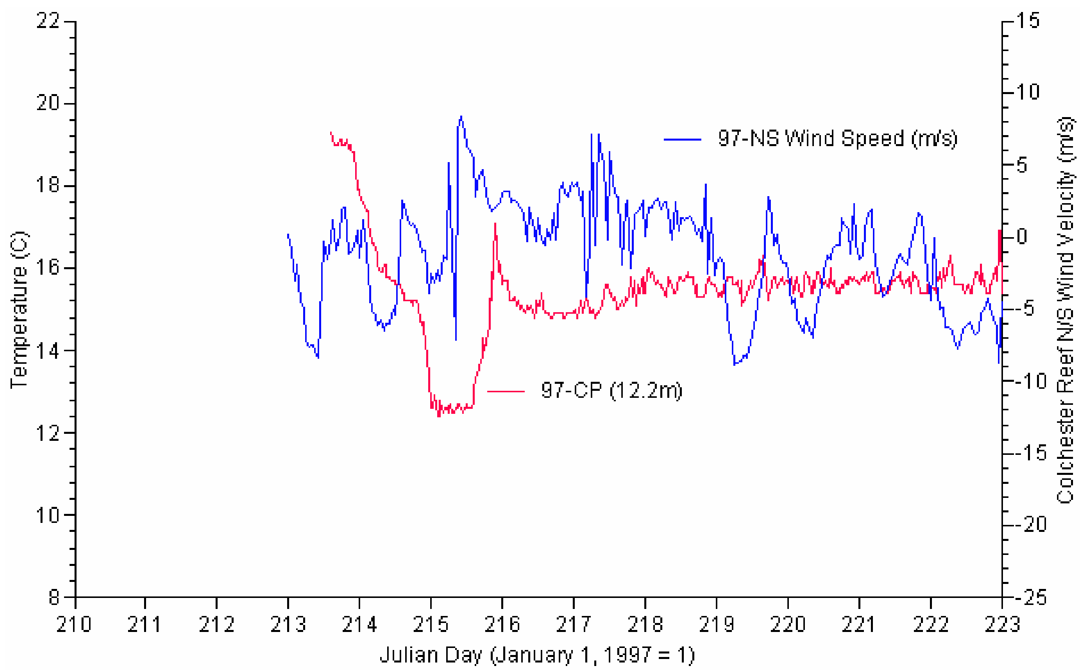

Figure 27. Expanded view of thermal hook event number 1 for 1997. N/S wind speed from Colchester Reef is provided for comparison. See text for further details.

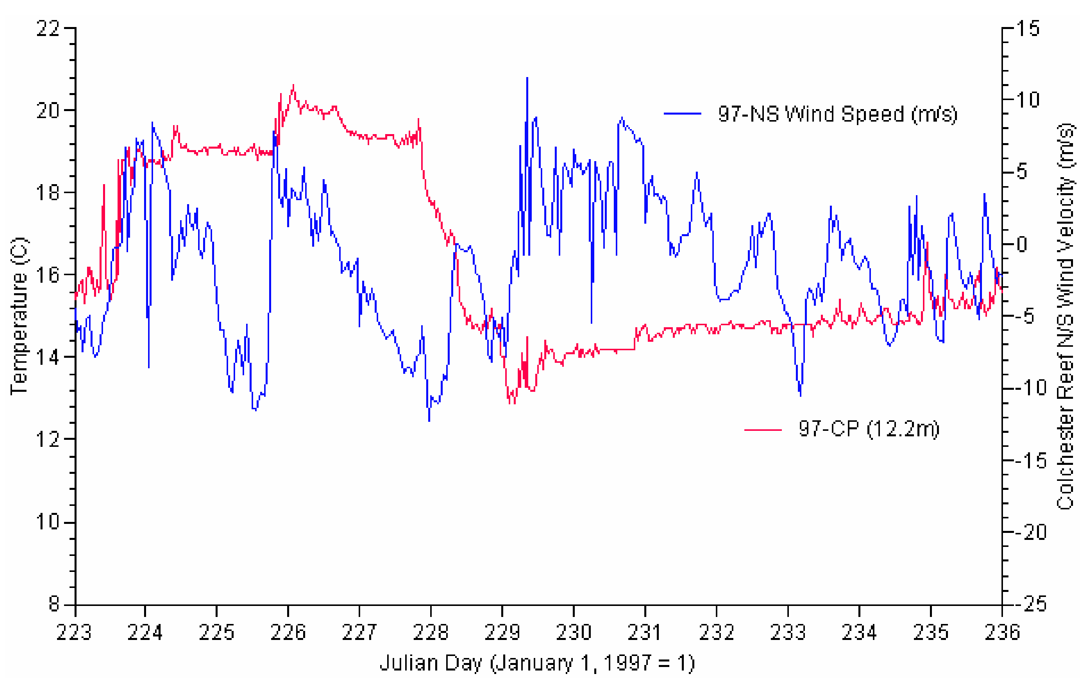

Figure 28. Expanded view of thermal hook event number 2 for 1997. N/S wind speed from Colchester Reef is provided for comparison. See text for further details.

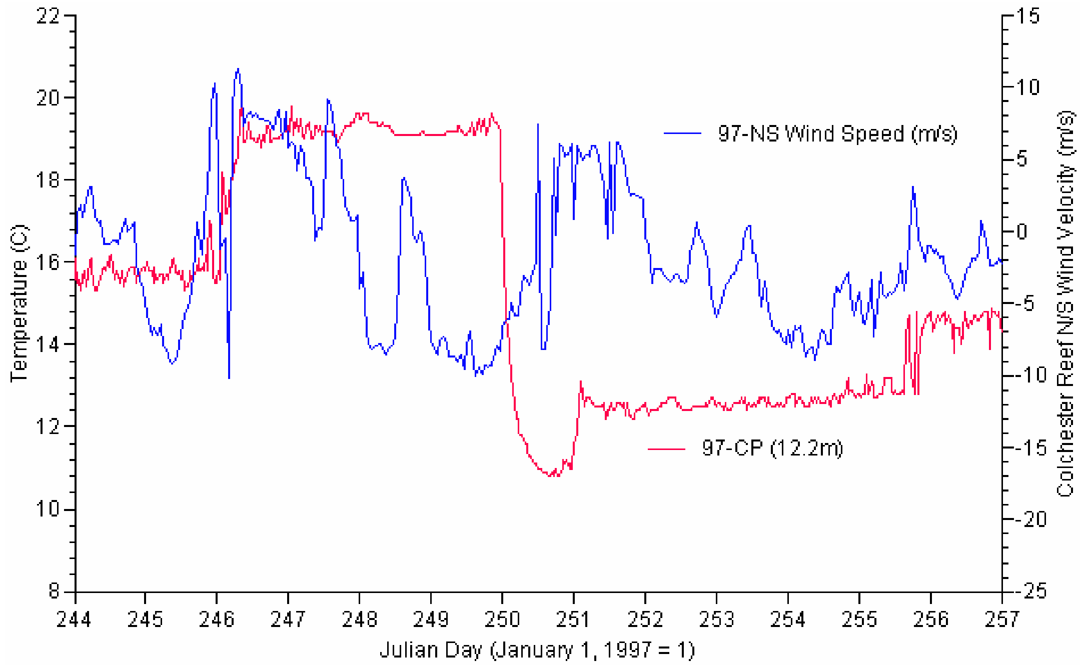

Figure 29. Expanded view of thermal hook event number 3 for 1997. N/S wind speed from Colchester Reef is provided for comparison. See text for further details.

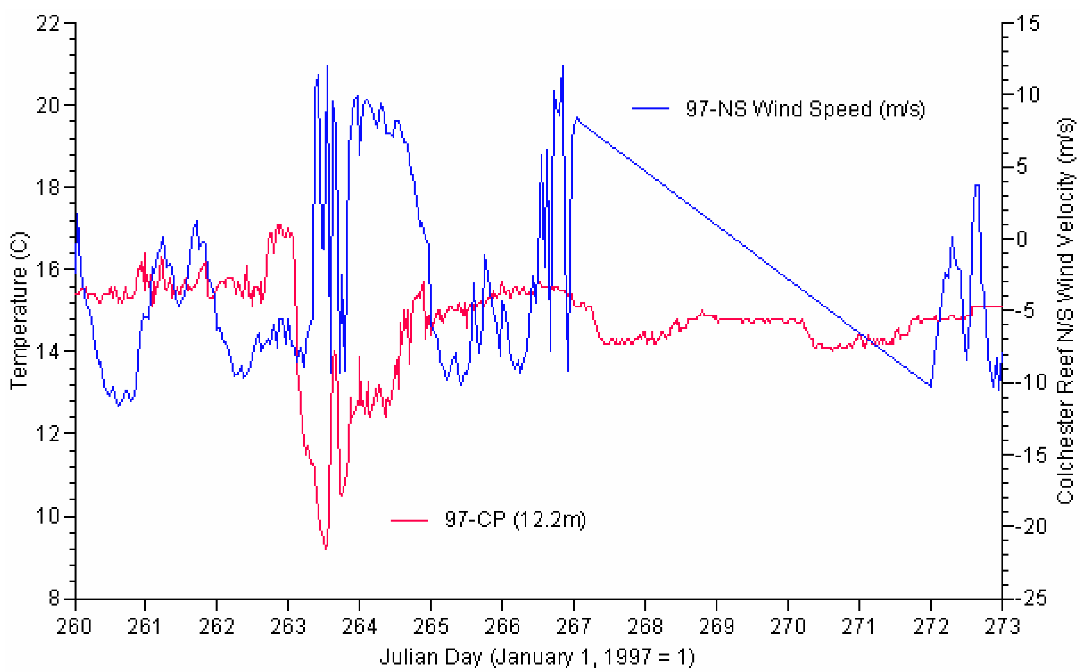

Figure 30. Expanded view of thermal hook event number 3 for 1997. N/S wind speed from Colchester Reef is provided for comparison. See text for further details. Note that straight lines fill data gaps.

Inter-annually, thermal variations can also be observed over the entire South Lake. For example, in 1997, observations from Benson Landing to Whitehall were thermally consistent to within ~ 2 ^{0}C. On the other hand, in 1998, a much wider range in temperature (maximum variation of ~11 ^{0}C) was evident at virtually all sites until atmospheric cooling dominated the thermal signatures in the South Lake. The same can also be stated for 1999, except that after day 220, the thermal signatures at all the sites were very consistent.

1997 ADCP Water Velocity Measurements

As previously mentioned, the RDI doghouse was situated on the western central pier of the Crown Point Bridge looking directly across channel to the eastern central pier. Measurements of along-channel and cross-channel water velocities as well as echo intensities were measured every 10 minutes for approximately 14 days. The bin-cell size was set at 1 meter with an initial offset of 2 meters. While there was a myriad of ways to display the data, the most useful for this report was smoothed, beam-averaged center-channel observations. The term beam-averaged reflects a 10-minute average of the four independent beams (see Figure12) into a final output of velocities (along- and cross-channel) in 1 m bins ranging from the sensor head. Additionally, only those observations taken from the center channel (i.e., approximately 5 to 50 meters from the ADCP) were used. Echo intensities suggested that at a depth of 21 feet and at 60 meters out, bottom topography or the eastern pier was being detected. Hence, the use of only those observations recorded within the central channel. Since observations were obtained every 10 minutes, an 8-hour boxcar filter was utilized on the data and subsequently sub-sampled every hour. The entire data set extended from midmorning on day 253 (11 September) to midday on day 267 (24 September). For analysis and plotting purposes, data were trimmed from day 254 to 267. It should be noted that Mr. Lee Gordon of RDI processed the ADCP data. These data were later provided in MATLAB format.

Figure 31 shows the results of the parameters monitored during this time period. Cross-channel velocity was the weakest of the two velocity components. The along-channel velocity possessed both higher amplitudes as well as bi-directional characteristics. Basic statistics for along-channel, cross-channel, and echo intensity are provided in Table 5. From this table, it can be seen that both velocity components had a median and average that were positive; reflecting an "eastward" directed cross-channel component as well as a northerly along-channel velocity. It should also be noted that the cross-channel velocity was routinely positive regardless of whether velocity was into or out of the South Lake (i.e., in the along-channel direction). While there is no historical information on velocity at the Crown Point Bridge, there is nevertheless a well-defined net northward velocity in the South Lake (Myer and Gruendling, 1979). This longer-term northward velocity in the South Lake agrees well with the along-channel average shown in Table 5.

Echo intensity, which is an indirect measure of the quantity of backscatterers in the water column, possessed a very strong diurnal signal. Although it is impossible to define whether these backscatterers are biological and/or sedimentological, the diurnal signal suggests that there may be a strong biological component. Diurnal migrations have been documented within Lake Champlain and specifically associated with upward looking ADCP measurements in the South Main Lake (Osterberg, 1999), and in Shelburne Bay (Sardilli, 1999).

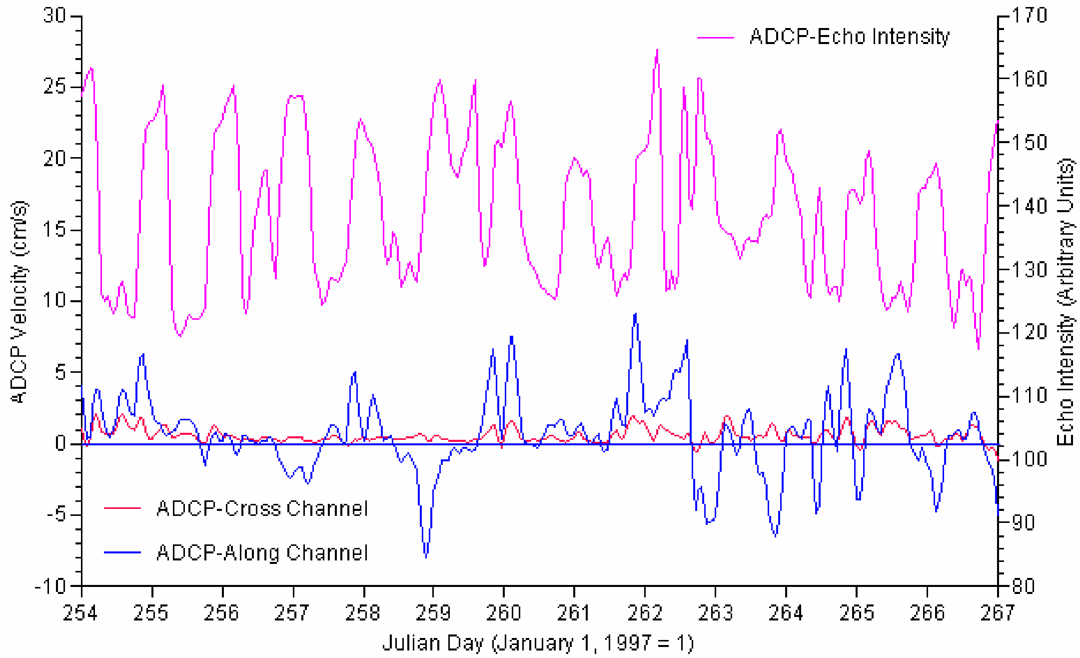

Figure 31 Doghouse records of a long-channel, cross-channel velocity as well as echo intensity for the duration of its and deployment.

Table 5. Statistical information obtained from the ADCP doghouse located on the western pier the Crown Point bridge at a depth of 21 feet. Results were from data collected within the center channel (5-50 meters). Velocities are in cm per second. Echo intensities are in arbitrary units.

Year	Parameter	Num.	Med.	Avg.	StdDev	Var.	Min.	Max.
1997	Speed (cross-channel)	313	0.5	0.6	0.5	2.5	-1.2	2.1
	Speed (along-channel)	313	0.6	0.6	2.8	7.7	-8.0	9.1
	Echo intensity	313	138	139	12	132.	117	165

Auto-spectra of the various parameters also show the dominance of long period oscillations (Table 6). The strongest component, in both the cross-channel and along-channel directions, reflects the more synoptic atmospheric patterns of 7.11 days. Most of the remaining spectral periods have been previously observed in auto- and cross-spectra with temperature loggers and atmospheric wind forcing with the exception of the 0.31 day (7.44 hours) peak found in the cross-channel component. Presently, this specific component is not well documented in any of the literature relating to Lake Champlain. It exceeds the longest surface seiche period of 4.2 hours by a factor of almost 2 and can therefore, not considered a component associated with surface oscillations of lake. Nor does it appear likely that this represents an east-west internal seiche oscillation at a latitude of Port Henry since the bottom bathymetry appears to be too shallow for this to exist. Investigation into the auto spectral records for BIA does, however, show the 0.30-0.32 day peak as the 13th strongest for both the east-west and north-south wind-speed components. Considering the removal of virtually all other forcing components, it becomes more plausible that this 0.31 spectral peak is atmospherically forced.

Table 6. First five significant periods (in descending order of power spectra magnitude) obtained from auto-spectral analysis of doghouse observations. Periods are given in days.

Year	Parameter	First	Second	Third	Fourth	Fifth
1997	Speed (cross channel)	7.11	1.78	2.67	0.31	1.42
	Speed (along channel)	7.11	1.94	2.37	3.56	0.85
	Echo intensity	0.97	2.67	0.85	0.50	1.33

The along-channel averaged-velocity data show no strong visual correlation with either the top (Figure 32) or bottom (Figure 33) temperature loggers at the Crown Point Bridge. Nor is there any apparent correlation with north-south winds recorded at Cholchester Reef (Figure 34). While this initially appears to be an unlikely situation, the answer appears to be associated with the depth of observation. As noted earlier, the depth of the ADCP was at 21 feet (6.4 meters) and therefore, most likely residing within the boundary of the metalimnion. As a result of this positioning, both upper and lower velocities (which may be opposed depending on the circumstances) would be observed by this instrument depending upon the elevation of the thermocline. A recommendation for future deployment of any current meter sites within the Crown Point bridge region would be that of having several side-looking ADCPs as well as a central upward looking ADCP. This would quantify any vertical current shears as well as average velocity in the upper and lower layers. From this type of information, reasonable estimates of volume flow into and out of the South Lake could be made.

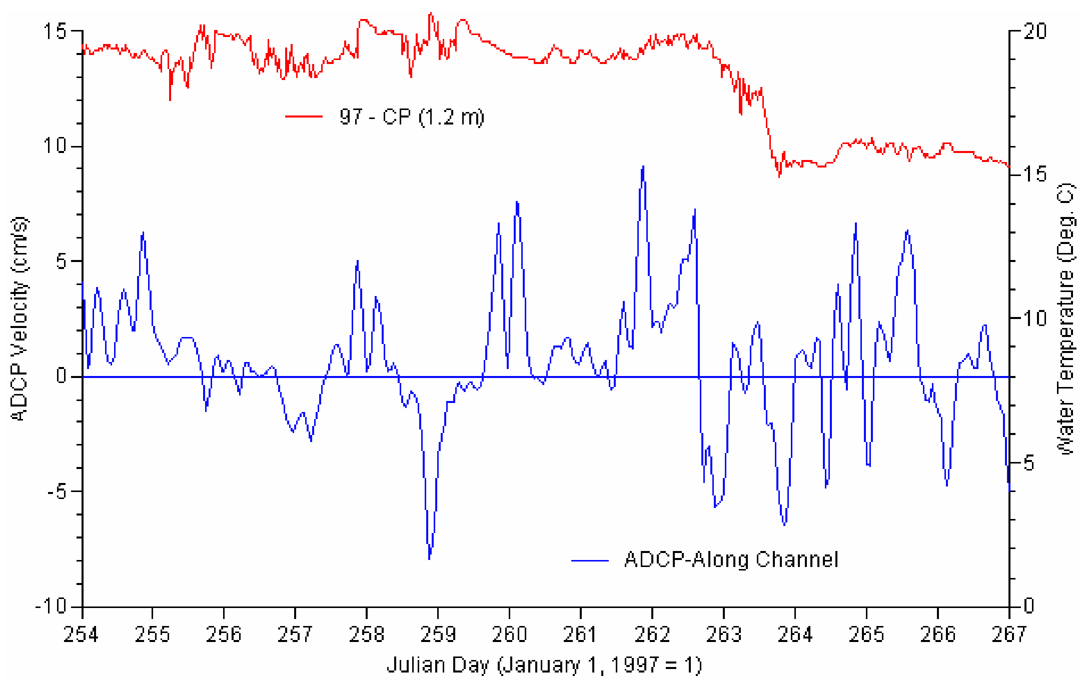

Figure 32. 1997 ADCP derived along-channel velocity compared to that of the top Crown Point temperature logger.

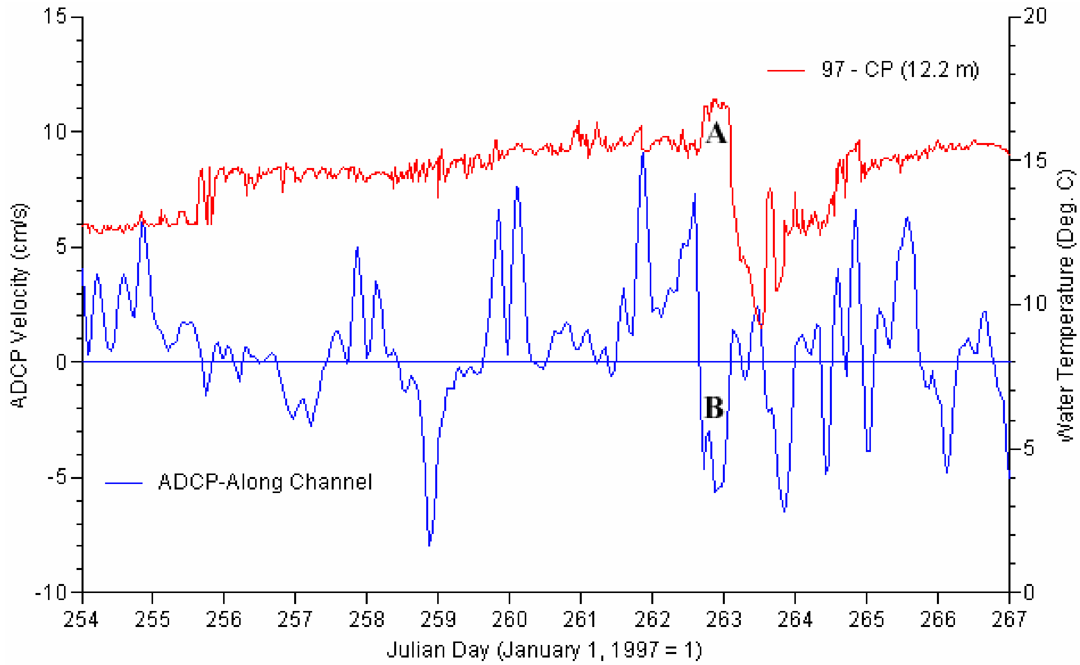

Figure 33. 1997 ADCP derived along-channel velocity compared to that of the bottom Crown Point temperature logger.

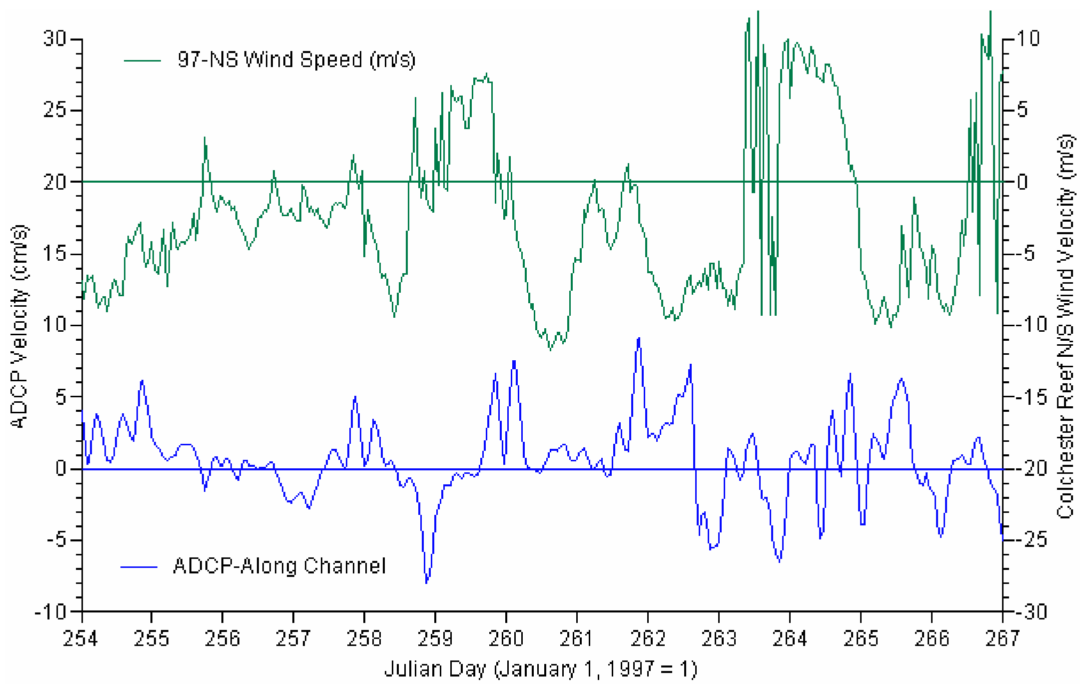

Figure 34. 1997 ADCP derived along-channel velocity compared to that of the north-south wind speed component at Cholchester Reef.

By chance, one of the thermal hook events occurred during the time period that the ADCP was located at the Crown Point bridge site. This particular event occurred near day 263 (Figure 30 & 33). The same deep temperature at Crown Point (12.2 meters) was also plotted against along-channel velocity in Figure 33. As with all thermal hook events, there is typically an increased temperature jump prior to the rapid drop in temperature. This warming event, labeled A in Figure 33, is in response to southerly-directed winds over the Main Lake. This forces warmer epilimnic water to the southern portion of the lake as well as depressing the thermocline to much deeper levels. In the case of the Crown Point region, a significant portion of the metalimnic and hypolimnic waters must been removed to account for this increased temperature in the deep water. Associated with this warmer epilimnic advance is a net southerly velocity. This southerly velocity is well correlated with the warm intrusion of epilimnic waters into the deep layers as can be seen in Figure 33 (labeled B). After a rapid change in wind direction from south-directed to north-directed (Figure 34), temperature dropped rapidly. During this transition period, water velocity shifted from south to north; in keeping with the onset of a southward propagating deep gravity current (not observed by the ADCP) and the compensating northward velocity (observed) of epilimnic water out of the South Lake.

For completeness, four separate images taken from Klein's (1999) movie depicting thermal oscillations in the South Main Lake during the same time period are provided in Figures 35, 36, 37, and 38. The upper portion of each figure defines a plan view location map (depth colored, purple being the deepest) of the various longterm moorings used in the 1997 field program. The first of these images (Figure 35; day 260.6250) shows a strongly depressed thermocline residing north of Potash Point as well as warmer epilimnic water occupying the shallow shelf to the south. This is in concert with a southerly flow of wind directed over the lake surface. One day later, the shelf break was being breached by the thermocline (Figure 36). On day 262.6250 (Figure 37), the internal gravity current (or propagation of the wave front defined by the thermocline) has already progressed past Mullen Bay. Seventeen hours later (Figure 38), the internal gravity current had moved past port Henry and the Crown Point Bridge. These observations agree very well with those of the side looking ADCP in that the first zero-velocity crossing after the initial warm-water pulse occurred at day 263.0833.

- Analysis -

Thermal variations at or near the lake surface are strongly linked to atmospheric forcing; specifically heating and cooling. In the deeper layers of the northern portion of the South Lake, heating and cooling cannot account for the large thermal variations associated with these thermal hooks. From the combined thermal information over the past three years, it is clear that these thermal hooks represent events forced by Main Lake dynamics. When looking more specifically at these events with expanded temporal scales (Figures 24, 25, and 26), a progression of each event to the south can be observed.

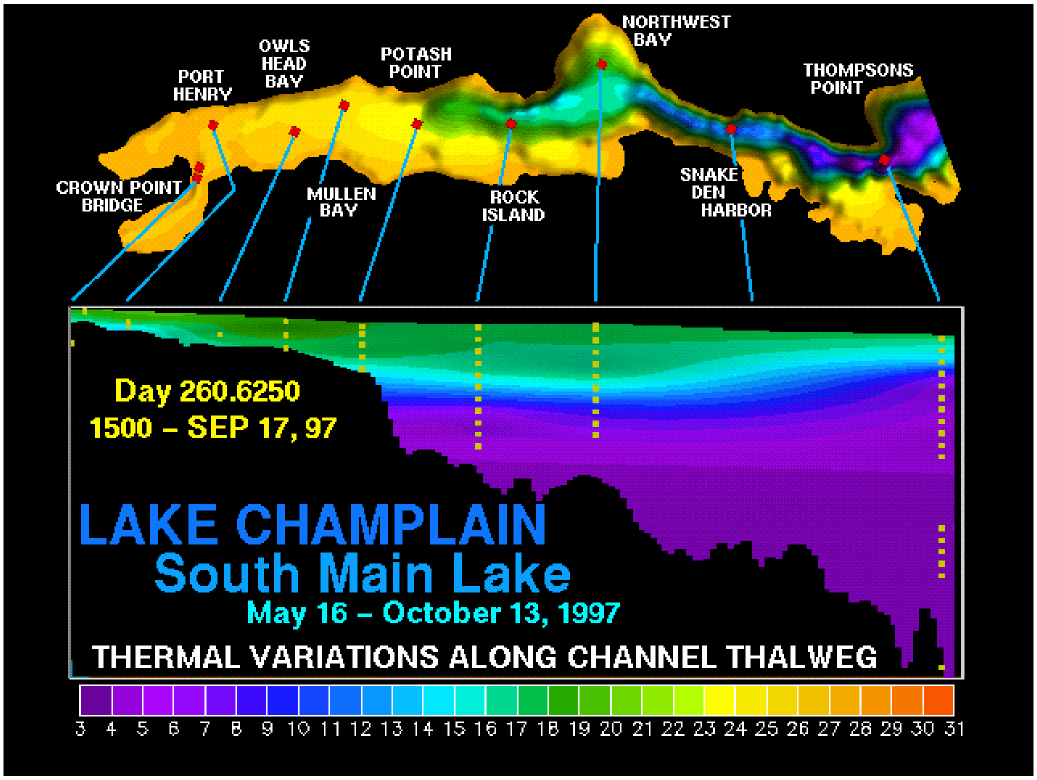

Figure 35. First of four images of the development of an internal gravity current created in the South Main Lake and propagating towards the Crown Point Bridge. Taken from Klein (1998). Note that the upper portion shows depth, with purple being deepest.

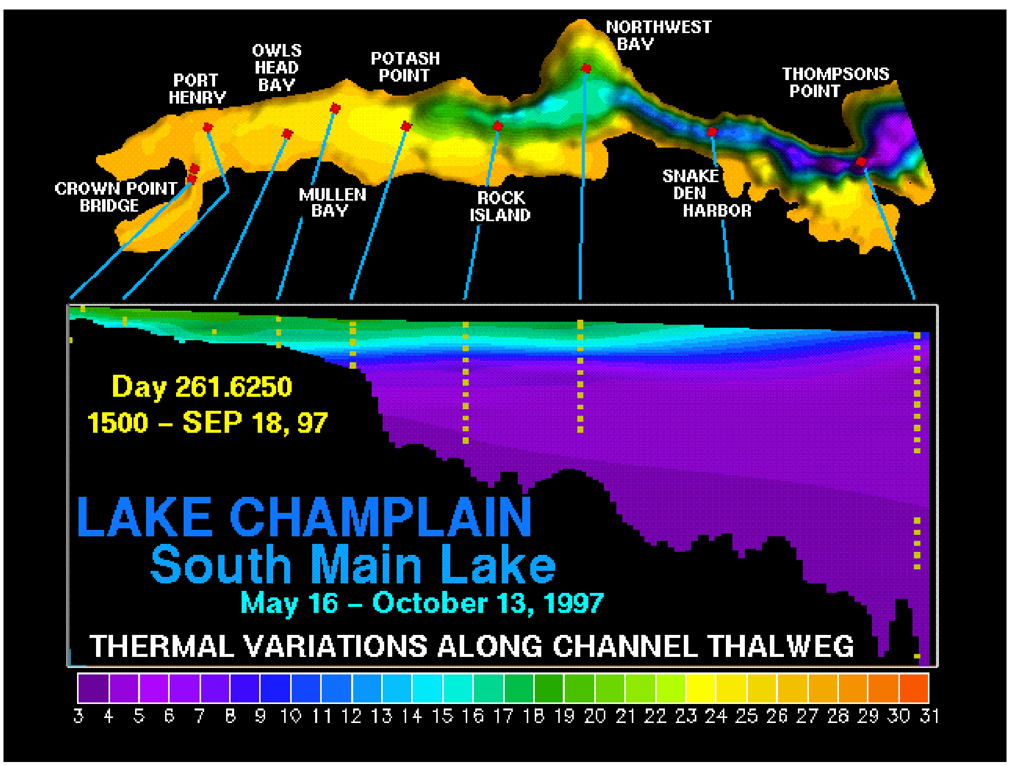

Figure 36. Second of four images of the development of an internal gravity current created in the South Main Lake and propagating towards the Crown Point Bridge. Taken from Klein (1998). Note that the upper portion shows depth, with purple being deepest.

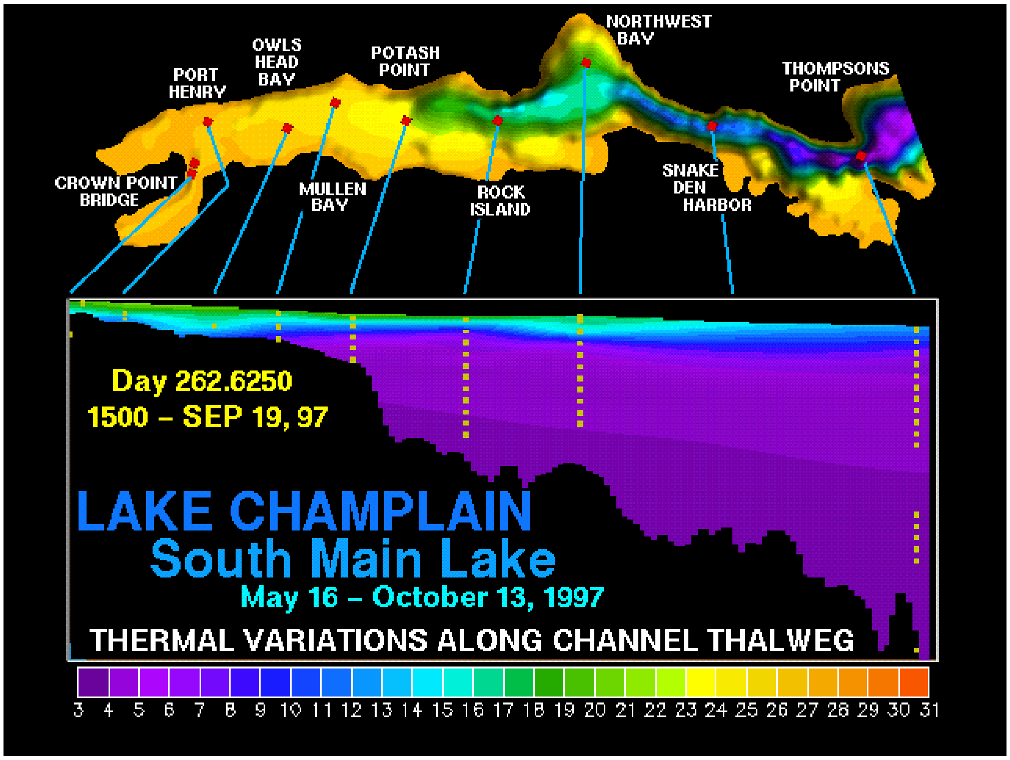

Figure 37. Third of four images of the development of an internal gravity current created in the South Main Lake and propagating towards the Crown Point Bridge. Taken from Klein (1998). Note that the upper portion shows depth, with purple being deepest.

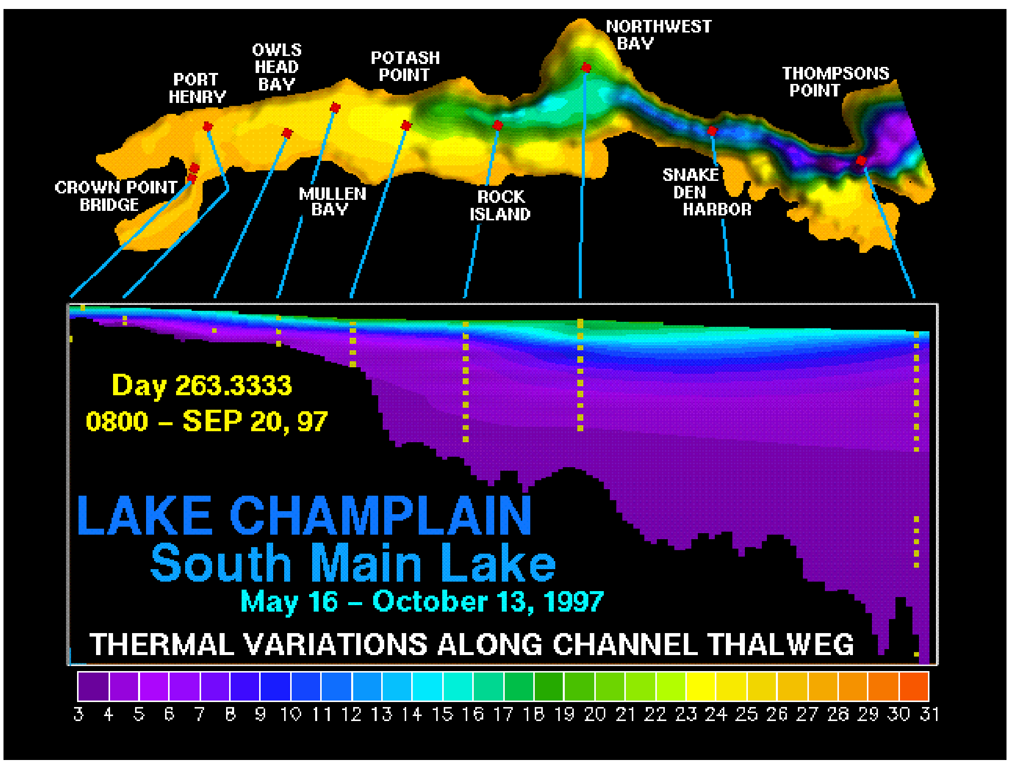

Figure 38. Last of four images of the development of an internal gravity current created in the South Main Lake and propagating towards the Crown Point Bridge. Taken from Klein (1998). Note that the upper portion shows depth, with purple being deepest.

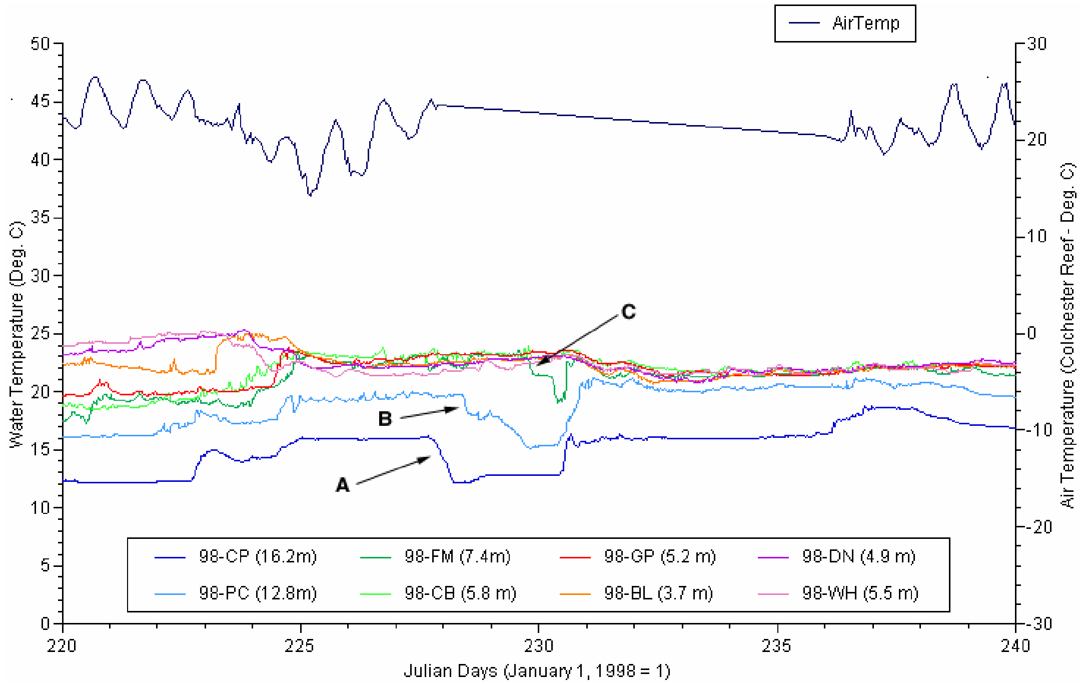

Figure 39. Bottom thermal data observed from day 220-240 during 1998. Note the large thermal hook pulse as it propagates from Crown Point through Putnam Creek and finally, at Five Mile Point. Note that straight lines fill data gaps.

From day 227 to day 230, a thermal pulse starting at the Crown Point Bridge can be seen to propagate southwards through the Putnam Creek site all the way to Five Mile Point (Figure 39;A, B, & C, respectively). The change in thermal signature over this distance of approximately 15 kilometers was primarily due to turbulent mixing and diffusion along its path. Very few thermal pulses have been observed to extend past Five Mile Point. Even then, it is not apparent that these anomalies past Five Mile Point represent those passing through the Crown Point Bridge.

Figure 40 shows two thermal hook pulses at Crown Point during days 203-205, and 210-211. The first event was observed to propagate all the way into five Mile Point (A, B, & C), however, the second event (D) had a significantly reduced thermal signature at Putnam Creek and none at Five Mile Point. Using the coldest value of the initial drop in temperature as a unique marker of the first event, propagation time from Crown Point to Putnam Creek was 33 hours (1.375 days). From Putnam Creek to Five Mile Point was an additional 31.92 hours (1.333 days).

Figure 41 also shows two more thermal hook pulses propagating southwards towards Five Mile Point. These particular pulses are unique in their thermal signatures and cannot be mistaken for other dynamic processes. It is worthwhile noting that both pulses propagated past Putnam Creek, but never reached Five Mile Point.

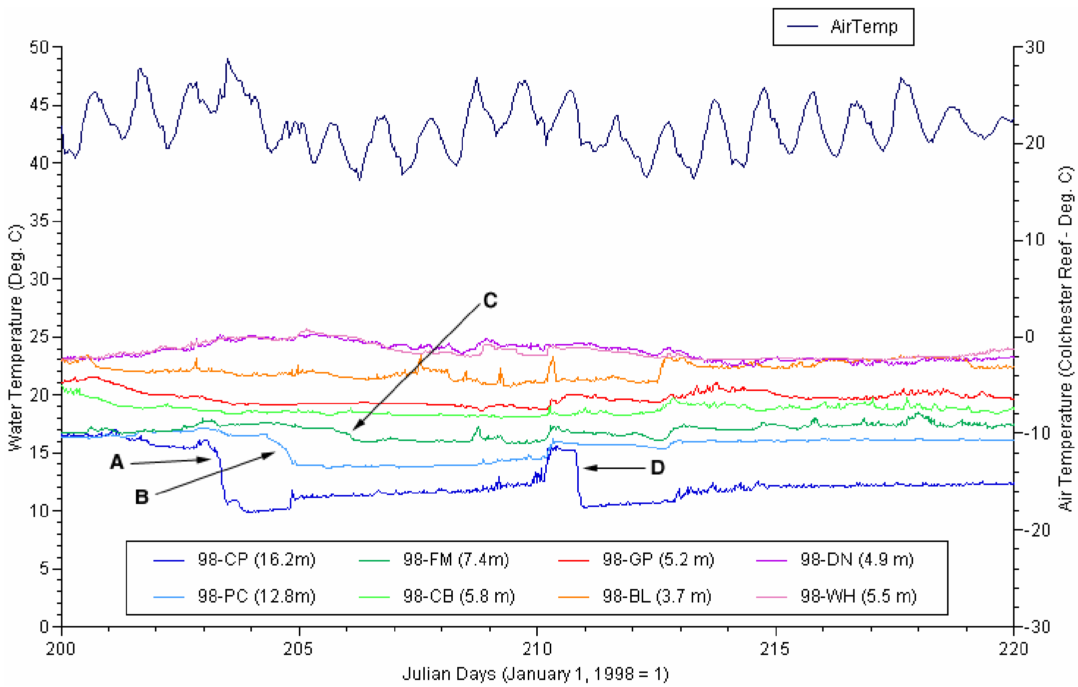

Figure 40. Bottom thermal data observed from day 200-220 during 1998. Two thermal hook pulses can be observed within this time. The first pulse propagates southward to Five Mile Point, however, the second one did not appear to have any propagation structure.

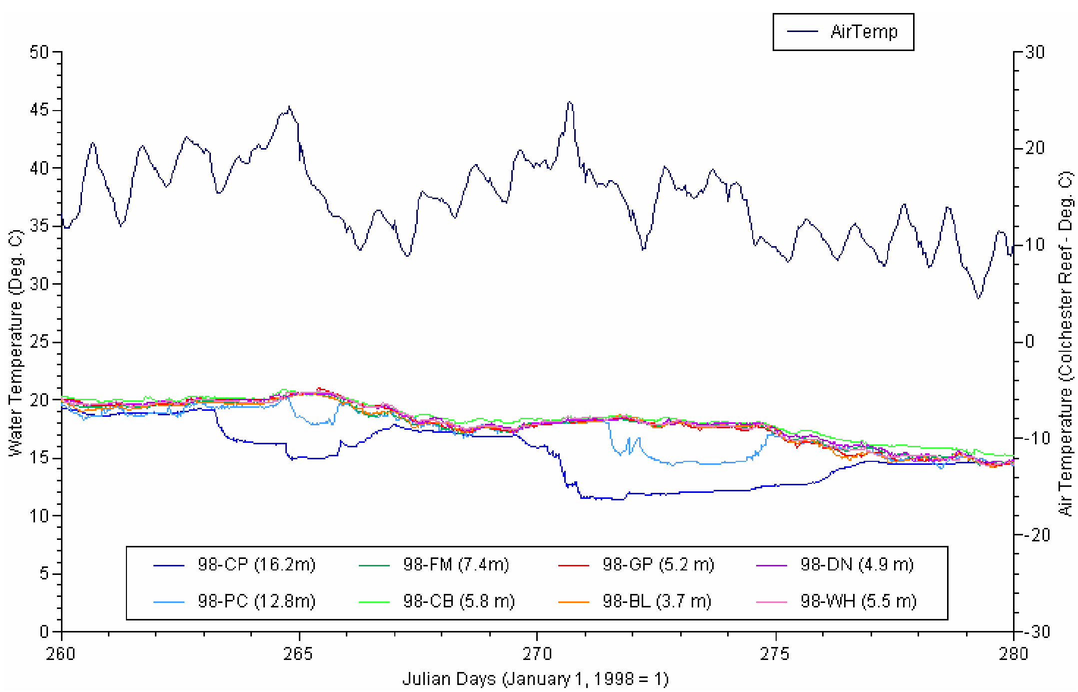

Figure 41. Bottom thermal data observed from day 260-280 during 1998. Two broad thermal hook pulses can be observed within this time frame. The first pulse propagates southward to Five Mile Point, however, the second one, even larger, did not reached Five Mile Point.

- Discussion -

From these observations, it is apparent that Main Lake forcing does have a significant impact on the northern portion of the South Lake. When combined with meteorological wind forcing (obtained from CR, BIA, and IPC), there is a consistent picture of strong north winds followed by relaxed or southerly winds. Northerly winds force warm epilimnic surface water to the south and hence, drop the thermocline in the northern portion of the South Lake dramatically. This in turn causes a large thermal increase in the deep-water observations. After the wind relaxes or reverses direction, warm surface water will be removed from the region as part of the relaxation phase of the Main Lake internal seiche and/or forced strongly to the north by southerly winds. It should be stressed that not all reversing wind events force hypolimnic water into the South Lake region. It takes not only the proper wind forcing but just as importantly, the proper phase relationship with the internal seiche, internal stratification, and potentially other internal dynamics within the Main Lake such as internal surges (Dr. K. Hunkins, recent unpublished modeling efforts in Lake Champlain). If this were not the case, then one would expect an internal gravity current propagating through the Crown Point Bridge approximately every 4.25 days in association with the uninodal internal seiche. When the proper conditions are met, however, metalimnic and hypolimnic water will then invade the deeper portions of the northern sector of the South Lake as internal gravity currents (Klein, 1998). Internal gravity currents have also been observed in the northern part of Lake Champlain (Saylor et al., 1999) but were much larger (lateral and vertical extent) than the thermal hook pulses observed in the South Lake.

Klein (1998) indicated that these non-linear internal gravity currents change shape as they approach shallower water, almost appearing as a near-vertical walls of cold water (see Figure 3) propagating along the bottom sediment-water interface at maximum observed speeds of 42 cm/s. The thermal hook pulses that were recorded at the Crown Point bridge site were primarily what one would expect to find with such an internal gravity current propagating past the site.

Yih (1980) developed a simplified equation of the propagation velocity (U) for internal gravity currents within a rectangular shaped basin as

$$U = .707\sqrt{(gd(\rho_2 - \rho_1)/(\rho_2 + \rho_1))}$$

where g is gravity, d is the average depth, and ρ_1 and ρ_2 are densities of the upper and lower layers, respectively. Using representative temperatures (densities) observed during the passage of a single thermal hook pulse at Crown Point and Five Mile Point, the propagation speed was determined to be 18 cm/s and 8 cm/s, respectively. Averaging these velocities produced a net travel time from the Crown Point Bridge to Five Mile Point of 32 hours. Observation times taken from the first thermal hook pulse in Figure 40 yielded a propagation time of nearly 65 hours. While this is in excess of the expected 32 hours, it appears to be well within the variability of accepted parameters of depth, bottom topography, and density variations over its path, as well as the simplified nature of this equation. If it were assumed that the average depth over its propagation path was closer to 6 m, rather than 9 m, which was used in the above determination, propagation time would double. This would then agree more favorably with the observations.

- Conclusions -

The South Lake, defined from a northern boundary of Crown Point Bridge to that of Whitehall at its southern boundary, represents several different hydrodynamic regimes. North of Five Mile Point, Main Lake internal seiche dynamics as well as local atmospheric forcing control flow dynamics. These combined forcing functions produce rapid influx of warm epilimnic water (thermocline depression) immediately followed by rapid intrusion of metalimnic/hypolimnic water. These intrusions represent internal gravity currents with steep leading faces as they passed the Crown Point Bridge. The characteristic thermal signature of these events passed through the Crown Point Bridge is that of a "thermal hook". Observations showed that the hypolimnic portion of the thermal hook pulse propagated at an average speed of approximately 8 cm/s over the distance from the Crown Point Bridge to Five Mile Point. Higher speeds, possibly approaching and upper limit of 42 cm/s (~ 1 knot) (Klein, 1998) might be expected at the Crown Point site. The average observed propagation velocity between Crown Point and Five Mile Point agrees well with the simplified model of internal gravity currents existing within a rectangular basin (Yih, 1980). ADCP data collected at the Crown Point Bridge indicated a maximum channel-averaged southward velocity of 5.7 cm/s during the southerly flow of epilimnic water past the Crown Point Bridge. It did not capture the deep southward velocity of the gravity current due to its shallow depth (6.4 m), but did define the time when flow reversal occurred.

Although it was expected that surface temperatures over the South Lake might be more uniform, this was not always the case. In 1997, Surface temperatures (excluding Crown Point and Putnam Creek) were very similar over the entire South Lake, however, in 1998 and 1999, surface temperatures varied considerably. These variations observed in the surface waters may indicate that the South Lake could be subdivided into separate environmental compartments.

Water level variations observed in 1997 and 1999 at Port Henry and at Whitehall showed very consistent results with each other. Visual correlation with north-south winds obtained at the CR/BIA and IPC meteorological station's was very strong. East-west wind forcing possessed much less correlation with water level data at both sites. The more restricted and southerly site, Whitehall, had much larger variations in water level than that of Port Henry. As was expected, Whitehall water level data showed an amplified appearance due to the shoaling and restricting affects of the narrow river environment.

The side looking ADCP mounted at the Crown Point bridge site at a depth of 6.4 meters provided a unique view of the integrated current structure across the center channel. The most dominant signature was that of along-channel velocity which possessed significant variability in flow direction. Cross-channel velocity, as expected, was small and not predominantly investigated in this report. Echo-intensities, which define the amount of particulates within the water column (backscatterers), showed an exceedingly strong diurnal component, which implied some type of biological activity.

Auto-and cross-spectral analyses were completed on all observations over all years. The most significant outcome was that the South Lake has preferred modes of oscillation that are directly linked to atmospheric forcing. Other than semi-diurnal and diurnal forcing events, oscillations within the South Lake range from 1.42-7.11 days. The 7.11 day spectral peak was the largest observed in both the along-channel and cross-channel velocities observed by the side-looking ADCP.

With regards to lake water quality, only a few speculations can be made at this time. First, it is possible that the bottom velocities obtained during these thermal hook events may have the capability to resuspend sediments and subsequently redistribute them both to the south and possibly back to the north (relaxation phase). In other circumstances where bottom velocities would not reach an erosional threshold, it is possible that clearer (less turbid), deep, hypolimnic water may be evident along the entire path length of the event. It should also be made clear that these intrusions are deep and often times well below the level of surface Secchi disk readings, and therefore, would not have a significant impact on the public’s perception of water clarity. To document whether or not these cases exist, longterm monitoring through the use of self-contained ADCPs, temperature sensors, and transmissometers would have to be made.

Recommendations for future Work relating to the South Lake would be that of a more rigorous set of water velocity observations in conjunction with thermal and water level variations. Meteorological observations for the South Lake should not rely upon CR or BIA due to their inability to properly define wind speed and direction within this reach of Lake. IPC or a similar site must be considered essential. If at all possible, water level observations should be completed along the South Lake rather than at the two endpoints. This would better afford any future researchers the ability to properly define propagation speeds of rapid changes in water level through the South Lake. The final culmination to such a research program within the South Lake would be that of a modeling effort that could eventually be linked to Main Lake dynamics.

Acknowledgments

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