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Analysis of Physical Oceanographic Data from Bonne Bay, September 2002 – September 2004

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Abstract

10 Acoustic Doppler Current Profilers were deployed between September 2002 and September 2004 on the sill of the East Arm in Bonne Bay, a glacial fjord in Gros Morne National Park on the west coast of Newfoundland. The moorings were deployed over the time period to measure the velocity of water flowing over the sill, in order to better understand the exchange dynamics of the system. In addition to the current meter data, several cruises were conducted in June 2004 to collect hydrographic data in the Bay, specifically temperature, salinity and density profiles. The data reveal the structure of the tidal flow over the sill and the interannual variability of the flow structure and transport. Meteorological data from the area are also presented.
Acknowledgements

We thank the crew and captain of the Louis M. Lauzier for their help in this oceanographic study. The hydrographic data were primarily collected by Drs. P. Snelgrove and D. Deibel. Funding for this project was provided from an NSERC Grant to B. de Young.
Table of Contents

Abstract.................................................................................................................. ii
Acknowledgements.......................................................................................... iii
Table of Contents.............................................................................................. iv
List of figures.................................................................................................... v
List of tables...................................................................................................... x
Introduction...................................................................................................... 1
Data processing................................................................................................. 2
References.......................................................................................................... 5
List of figures

Figure 1: Bathymetry of Bonne Bay .................................................................8
Figure 2: 2002 mooring positions .................................................................9
Figure 3: 2003 mooring positions ...............................................................10
Figure 4: 2004 mooring positions ...............................................................11
Figure 5: Low pass filtered ADCP data from mooring M1-2002. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity. .................................................................12
Figure 6: Low pass filtered ADCP data from mooring M2-2002. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity. .................................................................12
Figure 7: Low pass filtered ADCP data from mooring M3-2002. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity. .................................................................13
Figure 8: Low pass filtered ADCP data from mooring M4-2002. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity. .................................................................13
Figure 9: Low pass filtered ADCP data from mooring M1-2003. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity. .................................................................14
Figure 10: Low pass filtered ADCP data from mooring M2-2003. Cutoff is 30 hours.
   Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom:
   Spherically corrected backscatter intensity .........................................................14

Figure 11: Low pass filtered ADCP data from mooring M3-2003. Cutoff is 30 hours.
   Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom:
   Spherically corrected backscatter intensity. .........................................................15

Figure 12: Low pass filtered ADCP data from mooring M4-2003. Cutoff is 30 hours.
   Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom:
   Spherically corrected backscatter intensity. .........................................................15

Figure 13: Low pass filtered ADCP data from mooring M1-2004. Cutoff is 30 hours.
   Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom:
   Spherically corrected backscatter intensity. .........................................................16

Figure 14: Low pass filtered ADCP data from mooring M2-2004. Cutoff is 30 hours.
   Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom:
   Spherically corrected backscatter intensity. .........................................................16

Figure 15: Major axis angles for 2002 data at each depth bin calculated using Emery, 1997 pp 325. Angles are given in degrees, where 0° is East. The horizontal line indicates the bottom. .................................................................17

Figure 16: Major axis angles for 2003 data at each depth bin calculated using Emery, 1997 pp 325. Angles are given in degrees, where 0° is East. The horizontal line indicates the bottom. .................................................................17
Figure 17: Major axis angles for 2002 data at each depth bin calculated using Emery, 1997 pp 325. Angles are given in degrees, where 0° is East. The horizontal line indicates the bottom. ........................................................................................................18

Figure 18: ADCP data for M1-2002 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 15 ..............................................19

Figure 19: ADCP data for M2-2002 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 15 ..............................................19

Figure 20: ADCP data for M3-2002 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 15 ..............................................20

Figure 21: ADCP data for M4-2002 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 15 ..............................................20

Figure 22: ADCP data for M1-2003 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 16 ..............................................21

Figure 23: ADCP data for M2-2003 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 16 ..............................................21

Figure 24: ADCP data for M3-2003 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 16 ..............................................22

Figure 25: ADCP data for M4-2003 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 16 ..............................................22

Figure 26: ADCP data for M1-2004 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 17 ..............................................23

Figure 27: ADCP data for M2-2004 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 17 ..............................................23
Figure 28: Wind stress at Rocky Harbour over the period for which there is ADCP data.  
Calculated according to Gill 1982. .......................................................................24

Figure 29: Wind stress at Rocky Harbour from January 1993 to September 2004.  
Calculated according to Gill 1982. .......................................................................24

Figure 30: Air temperature at Rocky Harbour over the period for which there is ADCP  
data. White line is filtered with a cutoff of ~ 60 days. ........................................25

Figure 31: Air temperature at Rocky Harbour from January 1993 to June 2004. White  
line is a monthly average. .....................................................................................25

Figure 32: ADCP instrument temperatures for 2002. .......................................................26

Figure 33: ADCP instrument temperatures for 2003. .......................................................26

Figure 34: ADCP instrument temperatures for 2004. .......................................................27

Figure 35: Transect stations from June 6/7 2004. Vertical profiles were done at S1 and S4  
with a towed horizontal profile in between. ..........................................................28

Figure 36: Vertical and horizontal temperature, salinity and sigma-t profiles from S1 to  
S4, 16:10 to 16:36 GMT June 6 2004. ..................................................................29

Figure 37: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to  
S4, 17:42 to 18:09 GMT June 6 2004. ..................................................................30

Figure 38: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to  
S4, 19:37 to 20:01 GMT June 6 2004. ..................................................................31

Figure 39: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to  
S4, 3:30 to 3:55 GMT June 7 2004. ......................................................................32

Figure 40: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to  
S4, 6:23 to 6:45 GMT June 7 2004. ......................................................................33
Figure 41: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to S4, 8:21 to 8:50 GMT June 7 2004. .................................................................34

Figure 42: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to S4, 11:21 to 11:47 GMT June 7 2004. .................................................................35

Figure 43: South arm CTD stations and vertical transect line. ........................................36

Figure 44: Temperature, salinity and sigma-t along the South arm of Bonne Bay, June 2004. Numbers indicate CTD stations in Fig. 43. Stations 2 and 4 were collected June 9 2004, while stations 1, 3 and 5 were collected June 13 2004. This is the cause of the ‘bumpiness’ of the contours near the stations. .........................37

Figure 45: Sill-1 and Sill-2 positions from June 9 to June 11 .................................38

Figure 46: Temperature time series at Sill-1 and Sill-2. The middle plot indicates the tidal state. ..............................................................................................................37

Figure 47: Salinity time series at Sill-1 and Sill-2. The middle plot indicates the tidal state. ......................................................................................................................39

Figure 48: Sigma-t time series at Sill-1 and Sill-2. The middle plot indicates the tidal state. ......................................................................................................................39

Figure 49: East arm to Gulf of St. Lawrence CTD stations and vertical transect line ......40

Figure 50: Temperature, salinity and sigma-t over the sill of Bonne Bay, June 2004. Numbers indicate CTD stations. Stations 1-6 were collected on June 8 2004, while stations 7-10 were collected on June 13 2004. .................................................41
List of tables

Table 1: Location and Summary of Bonne Bay 2002-2004 ADCP moorings .................6
Table 2: Serial numbers and frequencies of Bonne Bay 2002-2004 moorings .............6
Table 3: Amplitude (cm/s) of the major axis of selected tidal constituents of the current at a depth of 1m .................................................................................................................................7
Table 4: Amplitude (cm/s) of the minor axis of selected tidal constituents of the current at a depth of 1m .................................................................................................................................7
Table 5: Phase (degrees relative to Greenwich) of selected tidal constituents of the current at a depth of 1m .................................................................................................................................7
Introduction

We are interested in the exchange over the sill of water between the east arm of Bonne Bay and the Gulf of St. Lawrence (see Figure 1). This exchange can be regulated by many different factors, including tides, wind stress, and freshwater runoff and largely determines the properties of deep water on the landward side of the sill.

The moorings were deployed on the sill to try and get a sense of the 3 dimensional nature of the flow. The 2002 and 2003 moorings were deployed directly on the bottom, while the 2004 moorings were about 1 metre above the bottom. The mooring positions for 2002, 2003 and 2004 are shown in Figures 2, 3 and 4. The moorings were arranged to provide the best coverage of the deepest part of the sill, approximately in the middle of it. Each ADCP was also equipped with a temperature sensor that measured the temperature of the water at the location of the instrument. The instruments were all RDI 4 beam sentinel ADCP’s at a frequency of 300 kHz, except for M1-2003 and M2-2003 which were 1200 kHz and 600 kHz respectively.

In addition to the current data, meteorological data were obtained from Environment Canada for the period from January 1993 to June 2004 for the nearby weather monitoring station at Rocky Harbour. Meteorological data for the summer of 2004 were obtained from a weather monitoring station installed on the roof of the Bonne Bay Marine Station.

Also, during June of 2004 several cruises were conducted to gather temperature, salinity, and density data in the area surrounding the sill, in the arms of the bay, and out into the Gulf of St. Lawrence. A cruise on June 6th and 7th collected vertical and
horizontal profiles on the sill over several tidal cycles. These data are presented as plots of temperature, salinity and $\sigma_T$ at and between the two stations on either side of the sill. A similar cruise was performed between June 9th and 11th, but without the horizontal surface profile. These data are plotted as time series contours.

Data Processing

The ADCP data were processed in a manner similar to the approach of Tittensor et al. 2002. First the data were extracted from the instrument output files and missing data was interpolated linearly from the data surrounding it. The data were collected in 1 metre depth bins for most instruments, though M1-2003 and M2-2003 were sampling with 0.5 metre bins. The backscatter was corrected following standard techniques (Deines, 1999) utilizing factory-set instrument characteristics as well as environmental factors such as the sound absorption coefficient and the speed of sound at each depth cell. These parameters, together with the slant range to each depth cell, were then used in the sonar equation to estimate the backscatter coefficient. The velocity was then decomposed into $u$ and $v$ components, and filtered using a 5th order forward and reverse Butterworth low pass digital filter with a cut-off of 30 hours (along with the backscatter) and plotted. The data were also corrected for the changing surface elevation due to tides by adjusting the data from each time step according to the level of maximum backscatter intensity. The filtered and surface-corrected data were then plotted.
The hourly wind and air temperature data for Rocky Harbour were obtained from Environment Canada as a series of text files. The data were examined for large peaks which were manually removed, and any short gaps were linearly interpolated. The data were extracted from these files, decomposed into $u$ and $v$ components, then converted to wind stress (Gill, 1982) and re-saved in a MATLAB format. The data set for 1997 from Rocky Harbour was incomplete and so was substituted with data from CornerBrook. Also, for a short period in 1999 the anemometer malfunctioned, but because this period did not correspond with ADCP data period it was ignored. Wind data for the period from June 19th to September 19th 2004 was obtained from a weather station installed at the Bonne Bay Marine Station. The data were extracted from text files and missing points were interpolated.

Vertical CTD profiles were collected using an SBE-25 probe, while the horizontal surface profiles were collected with an SBE-19 probe. Only the temperature, salinity and density data are presented here. The CTD data were extracted from the instrument output text files and re-saved in a MATLAB format. The up-cast portion was removed, as was the part of the data from when the instrument was sitting at the surface. The raw data were then plotted in several different ways. The data from the June 6th sill survey were plotted as vertical and horizontal profiles of temperature, salinity, and $\sigma_T$. The data from the June 9th sill survey were plotted as a time series contour at the two stations on either side of the sill. The data from the South Arm, East Arm, and out into the Gulf of St. Lawrence were plotted as two-dimensional vertical contour maps.

An analysis of the major axis direction for each mooring was performed (Emery, 1998) and the results are shown in Figures 15, 16 and 17. By solving for the eigenvalues
of the covariance matrix for the $u$ and $v$ velocities, the angle of the principle axis $\theta_p$ can be found using:

$$\tan(2\theta_p) = \frac{2u'v'}{u'^2 - v'^2}$$

where $u' = u - \bar{u}$ and $v' = v - \bar{v}$. The angles calculated through this process were then used to rotate the $u$ and $v$ axes for each depth at each mooring to visualize the through and cross channel velocities.

Tidal analysis for the moorings was performed using Foreman tidal analysis scripts for MATLAB (Pawlowicz, 2002) and the results for selected moorings are shown in Tables 2 and 3.
References


Table 1: Location and summary of Bonne Bay 2002-2004 ADCP moorings

<table>
<thead>
<tr>
<th>Mooring</th>
<th>Latitude (°N)</th>
<th>Longitude (°W)</th>
<th>Depth (m)</th>
<th>Averaging period</th>
<th>Bin size</th>
<th>Start day</th>
<th>End day</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1-2002</td>
<td>49 30.640</td>
<td>57 52.999</td>
<td>12</td>
<td>20 min</td>
<td>1m</td>
<td>Sept. 7</td>
<td>Nov. 21</td>
</tr>
<tr>
<td>M2-2002</td>
<td>49 30.769</td>
<td>57 53.002</td>
<td>27.4</td>
<td>20 min</td>
<td>1m</td>
<td>Nov. 22</td>
<td>July 17</td>
</tr>
<tr>
<td>M3-2002</td>
<td>49 30.757</td>
<td>57 53.002</td>
<td>27.4</td>
<td>20 min</td>
<td>1m</td>
<td>Sept. 7</td>
<td>June 6</td>
</tr>
<tr>
<td>M4-2002</td>
<td>49 30.816</td>
<td>57 52.954</td>
<td>15</td>
<td>20 min</td>
<td>1m</td>
<td>Sept. 7</td>
<td>Nov. 21</td>
</tr>
<tr>
<td>M1-2003</td>
<td>49 30.630</td>
<td>57 53.000</td>
<td>12.5</td>
<td>30 min</td>
<td>0.5m</td>
<td>Nov. 10</td>
<td>May 30</td>
</tr>
<tr>
<td>M2-2003</td>
<td>49 30.827</td>
<td>57 53.077</td>
<td>21</td>
<td>30 min</td>
<td>0.5m</td>
<td>Oct. 28</td>
<td>June 14</td>
</tr>
<tr>
<td>M3-2003</td>
<td>49 30.750</td>
<td>57 52.992</td>
<td>27.4</td>
<td>30 min</td>
<td>1m</td>
<td>Nov. 10</td>
<td>June 19</td>
</tr>
<tr>
<td>M4-2003</td>
<td>49 30.695</td>
<td>57 52.996</td>
<td>17.4</td>
<td>20 min</td>
<td>1m</td>
<td>July 19</td>
<td>Apr. 30</td>
</tr>
<tr>
<td>M1-2004</td>
<td>49 30.604</td>
<td>57 53.070</td>
<td>12</td>
<td>30 min</td>
<td>1m</td>
<td>June 16</td>
<td>Sept. 16</td>
</tr>
<tr>
<td>M2-2004</td>
<td>49 30.804</td>
<td>57 53.139</td>
<td>17</td>
<td>30 min</td>
<td>1m</td>
<td>June 16</td>
<td>Sept. 17</td>
</tr>
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Table 2: Serial numbers and frequencies of Bonne Bay 2002-2004 moorings.

<table>
<thead>
<tr>
<th>Mooring</th>
<th>Instrument Serial Number</th>
<th>Frequency</th>
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</thead>
<tbody>
<tr>
<td>M1-2002</td>
<td>2460</td>
<td>300 kHz</td>
</tr>
<tr>
<td>M2-2002</td>
<td>2477</td>
<td>300 kHz</td>
</tr>
<tr>
<td>M3-2002</td>
<td>2459</td>
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</tr>
<tr>
<td>M4-2002</td>
<td>0879</td>
<td>300 kHz</td>
</tr>
<tr>
<td>M1-2003</td>
<td>1336</td>
<td>1200 kHz</td>
</tr>
<tr>
<td>M2-2003</td>
<td>2069</td>
<td>600 kHz</td>
</tr>
<tr>
<td>M3-2003</td>
<td>2459</td>
<td>300 kHz</td>
</tr>
<tr>
<td>M4-2003</td>
<td>2477</td>
<td>300 kHz</td>
</tr>
<tr>
<td>M1-2004</td>
<td>2460</td>
<td>300 kHz</td>
</tr>
<tr>
<td>M2-2004</td>
<td>2477</td>
<td>300 kHz</td>
</tr>
</tbody>
</table>
Table 3: Amplitude (cm/s) of the major axis of selected tidal constituents of the current at a depth of 1m.

<table>
<thead>
<tr>
<th></th>
<th>M1-02</th>
<th>M2-02</th>
<th>M3-02</th>
<th>M4-02</th>
<th>M1-03</th>
<th>M2-03</th>
<th>M3-03</th>
<th>M4-03</th>
<th>M1-03</th>
<th>M2-03</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>3.293</td>
<td>1.483</td>
<td>1.769</td>
<td>3.843</td>
<td>1.678</td>
<td>1.149</td>
<td>0.602</td>
<td>2.464</td>
<td>2.719</td>
<td>2.937</td>
</tr>
<tr>
<td>K1</td>
<td>2.558</td>
<td>2.298</td>
<td>2.298</td>
<td>2.452</td>
<td>1.658</td>
<td>1.218</td>
<td>0.99</td>
<td>2.714</td>
<td>2.579</td>
<td>3.308</td>
</tr>
<tr>
<td>N2</td>
<td>4.074</td>
<td>2.968</td>
<td>2.9</td>
<td>4.221</td>
<td>2.997</td>
<td>2.055</td>
<td>1.647</td>
<td>3.62</td>
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<td>3.556</td>
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<td>K2</td>
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<td>2.624</td>
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<td>--</td>
<td>1.717</td>
<td>1.574</td>
<td>1.266</td>
<td>2.05</td>
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<td>--</td>
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<tr>
<td>M4</td>
<td>1.019</td>
<td>0.901</td>
<td>0.88</td>
<td>0.74</td>
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<td>0.607</td>
<td>0.269</td>
<td>0.799</td>
<td>4.037</td>
<td>2.493</td>
</tr>
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</table>

Table 4: Amplitude (cm/s) of the minor axis of selected tidal constituents of the current at a depth of 1m.

<table>
<thead>
<tr>
<th></th>
<th>M1-02</th>
<th>M2-02</th>
<th>M3-02</th>
<th>M4-02</th>
<th>M1-03</th>
<th>M2-03</th>
<th>M3-03</th>
<th>M4-03</th>
<th>M1-03</th>
<th>M2-03</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>-0.273</td>
<td>-0.164</td>
<td>-0.243</td>
<td>-0.196</td>
<td>-0.032</td>
<td>0.045</td>
<td>-0.021</td>
<td>0.017</td>
<td>0.016</td>
<td>0.043</td>
</tr>
<tr>
<td>K1</td>
<td>-0.025</td>
<td>0.033</td>
<td>-0.103</td>
<td>0.076</td>
<td>0.180</td>
<td>-0.042</td>
<td>0.203</td>
<td>0.012</td>
<td>-0.192</td>
<td>0.184</td>
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<tr>
<td>N2</td>
<td>-0.192</td>
<td>-0.079</td>
<td>-0.280</td>
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<td>0.099</td>
<td>0.094</td>
<td>-0.050</td>
<td>0.109</td>
<td>-0.023</td>
<td>-0.163</td>
</tr>
<tr>
<td>M2</td>
<td>-0.448</td>
<td>-0.016</td>
<td>-0.393</td>
<td>0.220</td>
<td>0.463</td>
<td>-0.022</td>
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<td>-0.369</td>
<td>-0.918</td>
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<tr>
<td>S2</td>
<td>-0.070</td>
<td>0.036</td>
<td>0.007</td>
<td>-0.064</td>
<td>-0.005</td>
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<td>0.158</td>
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<tr>
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<td>-0.062</td>
<td>-0.067</td>
<td>--</td>
<td>0.181</td>
<td>0.135</td>
<td>0.046</td>
<td>0.108</td>
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<tr>
<td>M4</td>
<td>-0.291</td>
<td>0.142</td>
<td>0.050</td>
<td>0.403</td>
<td>-0.029</td>
<td>0.164</td>
<td>0.044</td>
<td>-0.227</td>
<td>0.075</td>
<td>0.462</td>
</tr>
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</table>

Table 5: Phase (degrees relative to Greenwich) of selected tidal constituents of the current at a depth of 1m.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>5.6</td>
<td>263.81</td>
<td>194.03</td>
<td>101.96</td>
<td>324.44</td>
<td>184.51</td>
<td>246</td>
<td>346.69</td>
</tr>
<tr>
<td>K1</td>
<td>3.53</td>
<td>43.95</td>
<td>196.52</td>
<td>227.98</td>
<td>301.86</td>
<td>80.81</td>
<td>316.09</td>
<td>12.34</td>
</tr>
<tr>
<td>N2</td>
<td>20.25</td>
<td>269.54</td>
<td>53.06</td>
<td>87.66</td>
<td>92.12</td>
<td>122.93</td>
<td>191.82</td>
<td>202.43</td>
</tr>
<tr>
<td>M2</td>
<td>4.56</td>
<td>287.46</td>
<td>10.04</td>
<td>163.02</td>
<td>251.86</td>
<td>67.1</td>
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<td>16.94</td>
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<tr>
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<td>244.33</td>
<td>110.96</td>
<td>142.79</td>
<td>307.45</td>
<td>95.52</td>
<td>20.14</td>
<td>20.88</td>
</tr>
<tr>
<td>K2</td>
<td>--</td>
<td>85.51</td>
<td>220.7</td>
<td>--</td>
<td>54.76</td>
<td>180.84</td>
<td>110.61</td>
<td>248.2</td>
</tr>
<tr>
<td>M4</td>
<td>35.03</td>
<td>204.9</td>
<td>339.62</td>
<td>91.9</td>
<td>331.61</td>
<td>131.01</td>
<td>9.97</td>
<td>12.81</td>
</tr>
</tbody>
</table>
Figure 1: Bathymetry and topography of the Bonne Bay region. Bathymetry data obtained from the Geological Survey of Canada and the digitization of Chart 4658, topography data from the Shuttle Radar Topography Mission by the U.S. Geological Survey. Distance between grid points in the data set is approximately 4.3 metres.
Figure 2: 2002 mooring positions
Figure 3: 2003 mooring locations
Figure 4: 2004 mooring positions
Figure 5: Low pass filtered ADCP data from mooring M1-2002. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.

Figure 6: Low pass filtered ADCP data from mooring M2-2002. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.
Figure 7: Low pass filtered ADCP data from mooring M3-2002. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.

Figure 8: Low pass filtered ADCP data from mooring M4-2002. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.
Figure 9: Low pass filtered ADCP data from mooring M1-2003. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.

Figure 10: Low pass filtered ADCP data from mooring M2-2003. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.
Figure 11: Low pass filtered ADCP data from mooring M3-2003. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.

Figure 12: Low pass filtered ADCP data from mooring M4-2003. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.
Figure 13: Low pass filtered ADCP data from mooring M1-2004. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.

Figure 14: Low pass filtered ADCP data from mooring M2-2004. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.
Figure 15: Major axis angles for 2002 data at each depth bin calculated using Emery, 1997 pp 325. Angles are given in degrees, where 0° is East. The horizontal line indicates the bottom.

Figure 16: Major axis angles for 2003 data at each depth bin calculated using Emery, 1997 pp 325. Angles are given in degrees, where 0° is East. The horizontal line indicates the bottom.
Figure 17: Major axis angles for 2002 data at each depth bin calculated using Emery, 1997 pp 325. Angles are given in degrees, where 0° is East. The horizontal line indicates the bottom.
Through and cross channel low pass filtered ADCP data, M1-2002

Figure 18: ADCP data for M1-2002 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 15

Through and cross channel low pass filtered ADCP data, M2-2002

Figure 19: ADCP data for M2-2002 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 15
Through and cross channel low pass filtered ADCP data, M3-2002

**Figure 20:** ADCP data for M3-2002 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 15

Through and cross channel low pass filtered ADCP data, M4-2002

**Figure 21:** ADCP data for M4-2002 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 15
Figure 22: ADCP data for M1-2003 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 16

Figure 23: ADCP data for M2-2003 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 16
Figure 24: ADCP data for M3-2003 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 16

Figure 25: ADCP data for M4-2003 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 16
Through and cross channel low pass filtered ADCP data, M1-2004

![Image](https://example.com/image1.png)

**Figure 26:** ADCP data for M1-2004 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 17

Through and cross channel low pass filtered ADCP data, M2-2004

![Image](https://example.com/image2.png)

**Figure 27:** ADCP data for M2-2004 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 17
Figure 28: Wind stress at Rocky Harbour over the period for which there is ADCP data. Calculated according to Gill 1982.

Figure 29: Wind stress at Rocky Harbour from January 1993 to September 2004. Calculated according to Gill 1982.
Figure 30: Air temperature at Rocky Harbour over the period for which there is ADCP data. White line is filtered with a cutoff of ~ 60 days.

Figure 31: Air temperature at Rocky Harbour from January 1993 to June 2004. White line is a monthly average.
ADCP instrument temperatures in °C for 2002

Figure 32: ADCP instrument temperatures for 2002.

ADCP instrument temperatures in °C for 2003

Figure 33: ADCP instrument temperatures for 2003.
Figure 34: ADCP instrument temperatures for 2004.
Figure 35: Transect stations from June 6/7 2004. Vertical profiles were done at S1 and S4 with a towed horizontal profile in between.
Figure 36: Vertical and horizontal temperature, salinity and sigma-t profiles from S1 to S4, 16:10 to 16:36 GMT June 6 2004.
Figure 37: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to S4, 17:42 to 18:09 GMT June 6 2004.
Figure 38: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to S4, 19:37 to 20:01 GMT June 6 2004.
Figure 39: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to S4, 3:30 to 3:55 GMT June 7 2004.
Figure 40: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to S4, 6:23 to 6:45 GMT June 7 2004.
T, S, and $\sigma_T$ for Section 6 - 8:21 to 8:50 (GMT) June 7 2004

Figure 41: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to S4, 8:21 to 8:50 GMT June 7 2004.
Figure 42: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to S4, 11:21 to 11:47 GMT June 7 2004.
Figure 43: South arm CTD stations and vertical transect line.
Figure 44: Temperature, salinity and sigma-\(\tau\) along the South arm of Bonne Bay, June 2004. Numbers indicate CTD stations in Fig. 43. Stations 2 and 4 were collected June 9 2004, while stations 1, 3 and 5 were collected June 13 2004. This is the cause of the ‘bumpiness’ of the contours near the stations.
Figure 45: Sill-1 and Sill-2 positions from June 9 to June 11.

Figure 46: Temperature time series at Sill-1 and Sill-2. The middle plot indicates the tidal state.
Figure 47: Salinity time series at Sill-1 and Sill-2. The middle plot indicates the tidal state.

Figure 48: Sigma-t time series at Sill-1 and Sill-2. The middle plot indicates the tidal state.
Figure 49: East arm to Gulf of St. Lawrence CTD stations and vertical transect line
Figure 50: Temperature, salinity and sigma-t over the sill of Bonne Bay, June 2004. Numbers indicate CTD stations. Stations 1-6 were collected on June 8 2004, while stations 7-10 were collected on June 13 2004.