Summary of Ocean Current Statistics for the Cable Crossing at the Strait of Belle Isle

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Table of Contents

Table of Figures

Table of Tables

1.0 Introduction

The Strait of Belle Isle is one of two straits, including the Cabot Strait, that connect the Gulf of St. Lawrence to the North Atlantic Ocean. The Strait is approximately 16 km wide at the narrowest crossing and lies between the Labrador coast to the north at Amour Point and the Newfoundland coast to the south at Savage Point. Its deepest point is just over 100 m.

The previously issued report, titled “Physical Environmental Description for the Cable Crossing at the Strait of Belle Isle, Cabot Strait and Northumberland Strait”, describes in detail the Oceanography and Meteorology in the region of interest. The aim of the research presented in the following report is to review and summarize the available ocean current data, and to produce best estimates of the mean and maximum expected current speeds along the corridor route, including periods during the year when current measurements are lacking.

The following section describes the data sources and methods used to produce the current estimates, along with explanations and definitions of the uncertainty terms and their sources. A statistical summary of the measured current speed per season and depth level are also included in Section 2. In Section 3 the statistical estimates are presented, accompanied with instructions for their interpretation based on the specific computational methods used. Mean and maximum expected current speed estimates are provided for each season, at three depth levels (near surface, mid-depth and near-bottom).

2.0 Data and Methods of Analysis

2.1. Data sources

The ODI (Ocean Data Inventory) Currents Database (BIO, 2010) contains the most comprehensive set of current measurements in the Strait of Belle Isle, consisting of data that have been recorded during several field programs conducted by the Bedford Institute of Oceanography (BIO) in 1963, 1975 and 1980. The measurements were conducted in an area coinciding or adjacent to the proposed cable routes, along a line spanning the whole cross section of the Strait (see Figure 2.1), generally at near-surface and mid-depth levels. The raw time series from this database were the primary data source from which the tidal and low-frequency non-tidal constituents were extracted. This enabled the modelling of yearly tidal currents during periods when no actual data had been collected, as well as estimating the magnitude of non-tidal current components that are generally associated with events of large-scale atmospheric forcing.

In order to investigate the variability of currents with cross-strait distance and depth, three horizontal sectors (north, center and south) and three depth levels (near-surface, mid-depth and near-bottom) have been defined. The data points have been allocated to the corresponding spatial sector based on their location and depth relative to the water depth at their location. Thus, data from depths in the range of 0-25 m has been classified as ‘near surface’; the range of 40-55 m has been classified as ‘mid-depth’ for all points except those in the center of the Strait where the water depth is close to 55 m; the range of 0-15 m from the bottom has been classified as ‘near-bottom’. The seasons have been defined in the following way: December to February constitutes winter; March to May constitutes spring; June to August constitutes summer; September to November constitutes fall.

A review of the current literature and additional data sources revealed that a field program was conducted from 10 January to 6 November 2004, in the central part of the Strait near the corridor route, the results of which were presented by Galbraith (2006). Current data were collected at a depth of 105 m (6 m off the bottom) from January to October. The along-channel current speed data presented by Galbraith (2006) were taken into account in the procedure for estimating the magnitude of the non-tidal forcing during the winter, spring and summer seasons. Several attempts were made to gain access to the raw data, however for unknown reasons the dataset had not been integrated into the ODI Currents Database and it was not available through the Data Services department of the DFO (Department of Fisheries and Oceans) at the time of writing of this report.

The locations of the current meter measurements used in this report are presented in Figure 2.1.

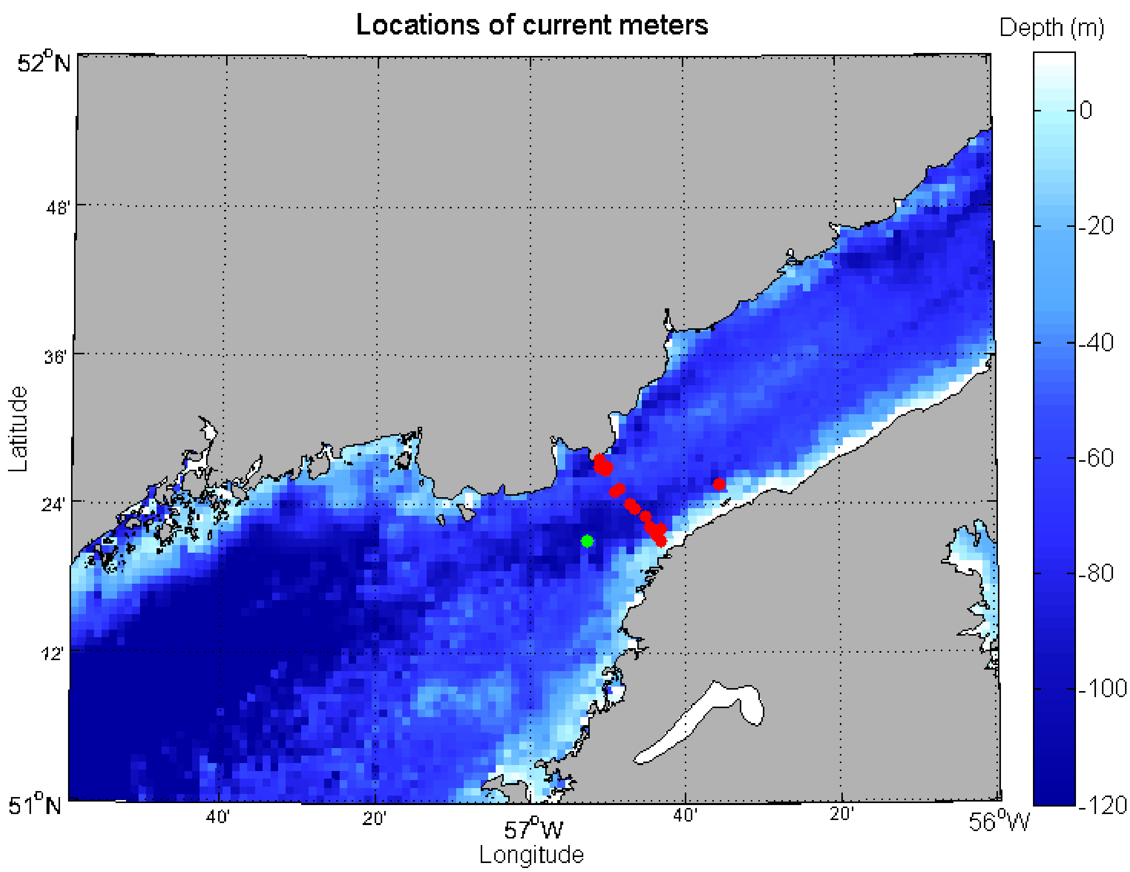

Figure 2.1 Locations of moored current meters. The red dots represent the near-surface and mid-depth current meters deployed in the field programs of BIO (1963-1980); the green dot represents the location of near-bottom measurements by Galbraith (2006).

In the following Tables 2.1 and 2.2, the summaries of mean and maximum current speeds measured in the field programs by BIO (2010) are presented per depth level and season. Maximum speeds reported in proprietary reports were considered and included in the table when they were in excess of those derived from the BIO(2010) measurements. As the raw data from SNC-Lavalin (1982) and NORDCO Ltd. (1978) were not available, the mean current statistics were only reported from BIO (2010).

It is apparent that the mid-depth and bottom levels are not sampled in the winter and spring seasons. These measurements allow for only a limited view of the flow in the Strait of Belle Isle based on observations during short periods of time in three different years (1963, 1975 and 1980), thus they do not represent robust estimates of the mean and maximum expected current speeds. The following subsection describes the approach taken in order to produce more robust estimates of the currents in the Strait of Belle Isle, including the seasons and depth levels that have not been sampled during the field programs.

Maximum Current Speed [ms^{-1}] Derived from measurements.					
		WINTER	SPRING	SUMMER	FALL
DEPTH	Surface	1.8	2.0	2.6	2.5
	Mid-Depth	-	-	2.0	1.8
	Bottom	-	-	1.6*	2.0**

Table.2.1 Measured maximum current speeds for the four seasons, at three depth levels (BIO, 2010). The highest near-bottom currents in the summer (*) were observed by SNC-Lavalin (1982); the highest near-bottom currents in the fall (**) were observed by NORDCO Ltd. (1978).

Mean Current Speed [ms^{-1}] Derived from BIO (2010)					
		WINTER	SPRING	SUMMER	FALL
DEPTH	Surface	0.5	0.5	0.6	0.5
	Mid-Depth	-	-	0.5	0.4
	Bottom	-	-	0.4	0.4

Table 2.2 Measured mean current speeds for the four seasons, at three depth levels (BIO, 2010).

2.2. Methods of Analysis

There are two main challenges in producing robust estimates of the maximum expected current magnitudes in the Strait of Belle Isle. First, the available current measurements were recorded mostly during the summer and fall seasons, but data for the winter and spring seasons, as well as near the bottom, were lacking. Second, the measurements represent snapshots of the currents in particular years (1963, 1975, and 1980), in a region where the mean flow can vary significantly from year to year, as shown in the studies by Garret and Petrie (1981), Petrie et al. (1988) and Galbraith (2006). Therefore, the maximum observed currents during the relatively well-sampled seasons may underestimate the maximum currents that occur in the Strait during years when the long-term mean flow is higher.

In response to these challenges, the approach taken in this report has been to understand the underlying processes contributing to the flow in the Strait based on the available data, and to model or project best estimates for all processes during all four seasons. The three main processes contributing toward the flow in the Strait are: the tides; non-tidal processes acting on the order of several days, associated with meteorological forcing; long-term (interannual) variability of the mean flow associated with the general circulation of the world oceans. The projected contributions from these three processes have been added in the final estimates presented in Section 3.

The following subsections describe the procedure followed for each type of analysis.

2.2.1. Tidal Analysis

The analysis of tidal components was performed at each of the depths and cross-strait locations where suitable current speed time series were available. Initial analyses indicated that continuous records with durations of at least one month were necessary in order to properly extract the tidal contribution to the currents. At least one or several time series longer than 2 months were available for each of the cross-strait sections (north, center, south), at near-surface and mid-depth levels. The data were sampled at intervals of 5 or 30 minutes, providing a sufficiently high resolution for this analysis.

The tidal constituents were extracted by performing classical harmonic analysis using the T_TIDE analytical package for Matlab (Pawlowicz et al., 2002). The analysis revealed the dominant constituents, as well as the associated signal to noise ratio and uncertainties. In a following step, the coefficients of the tidal constituents were used to produce modeled hourly time series of the tidal currents for the full year of each deployment, including the periods when measurements were not available. The mean and maximum value of the modeled tidal currents from each set of coefficients was selected as the tidal contribution to the mean and maximum expected currents, respectively. Due to the fact that the tidal forces originate from the celestial bodies and are not strictly a function of the four seasons, the calculated yearly maximum values at a given location and depth can be considered as the highest estimate of the tidal currents at any time of the year.

There were no available near-bottom current time series of sufficient length to extract reliable tidal coefficients, therefore it was necessary to extrapolate the surface and mid-depth estimates down to the near-bottom level. The study of Toulany et al. (1987) indicated that the current amplitude at the bottom of the Strait is generally reduced to 50-60 % of the surface values at low frequencies (4-8 days), and to 80-100% of the surface values at higher frequencies (less than 4 days). Since the main tidal constituents are the semidiurnal and diurnal tides, the tidal currents near the bottom are expected to be in the 80-100% range of the surface values. Based on the observed variation from the near-surface to the mid-depth level, the value of the surface tidal currents was used for the near-bottom level.

The tides represent the best understood process influencing the flow, and they can be predicted with a good degree of certainty. The inherent uncertainty of the tidal predictions arises from the individual uncertainties in accounting for each of the tidal components. While the main semidiurnal and diurnal constituents were generally resolved to certainty of a few millimeters per second, the less dominant constituents had a relatively bigger margin of error. The combined uncertainty from all tidal constituents amounted to an error of 0.1 ms^{-1}, for values of the tidal currents on the order of 1 ms^{-1}.

2.2.2. Non-tidal Components of Current Speed

The tidal analysis indicates that tidal forcing plays a major part in the observed currents in the Strait of Belle Isle. However, in all cases, a significant part of the signal could not be accounted for by the tides, therefore it was necessary to quantify the non-tidal component of the currents. For this purpose, it was found adequate to resample the original time series by using a succession of passes with a Finite Impulse Response (FIR) filter, resulting in a sampling rate of one sample per 24 hours. This made it possible to capture the contribution from meteorological events typically on the time scale of several days, while vastly eliminating the influence of the tides.

For this part of the analysis, all the available time series were used in order to capture every recorded event of atmospheric forcing. The mean and maximum non-tidal values at each location and depth level were selected for consideration in estimating the mean and maximum expected current speeds. Despite the fact that the raw data from the field program by Galbraith (2006) was not available, the non-tidal (25 h averaged) near-bottom current time series spanning from January to May was utilized to obtain estimates for the non-tidal components of the current speed near the bottom.

A comparison of the time series of several neighbouring sites where the currents were measured simultaneously allowed us to estimate the uncertainty in capturing the effect of any particular forcing event on the measured currents. Thus, the standard deviation of the difference in measured speed between neighbouring sites gives an estimated error of 0.3 ms^{-1} for the non-tidal components of the current speed. The magnitude of the current contribution associated with atmospheric forcing was on the order of 1 ms^{-1}.

2.2.3. Inter-annual variability of the general circulation

While continuous, multi-year measurements of current speed in the Strait of Belle Isle are not available, the sea levels have been recorded by tide gauges at permanent stations on both sides of the Strait over continuous periods of several years. These measurements have allowed researchers to compute the slope of the water surface across the Strait for these periods of time. Garrett and Petrie (1981) investigated sea slope measurements coinciding with current measurements in 1963. They found that the along-strait mean surface flow speeds were directly related to the sea level slope measured across the Strait, due to the effects of the Earth's rotation. In oceanographic terms, the mean flow in the Strait is said to be in geostrophic balance. In absence of stratification (when water density remains constant with depth) the relationship is not only valid for surface currents but for currents over the entire water column. In the presence of stratification, the increase of density with depth is associated with vertical shear in the vertical current profile.

This property of the mean flow in the Strait can be exploited to derive estimates of the mean flow speeds purely from tide gauge data. Right after calibration and deployment of the gauges, the difference in water level measured across the Strait can directly be translated into a geostrophic mean current along the Strait. A cross Strait water level difference of zero corresponds to a speed of zero for the geostrophic current along the Strait. However, the vertical reference of tide gauges tends to drift apart from each other over time. This introduces a bias in the relationship between cross Strait water level difference and geostrophic current: the gauges report different water levels across the Strait when the mean current speed is zero and the difference is the bias introduced by the drift of the vertical references. If current measurements are conducted at a point in time this bias, can be estimated and the relationship between cross Strait water level difference and mean geostrophic current along the Strait can be re-established.

Garrett and Petrie (1981) compiled sea level measurements from 8 consecutive years (1970-1977) and derived an 8 year time series of monthly means of the water level differences across the Strait. For each of the twelve months, they computed the 8-year average of the monthly means, which indicates a significant seasonal variability of the mean geostrophic flow along the Strait. They also gave the minimum and maximum monthly mean over the 8 years, which shows the range of the inter-annual variability of the mean flow. Petrie et al. (1988) reanalyzed the data presented by Garrett and Petrie (1981), taking into account simultaneous sea level and current measurements from 1980, which allowed for "geostrophic leveling" of the tide gauge data. They found that summer 1980 saw below-average mean flow in the Strait. Based on the mean and the variance of the seasonal current estimates presented in these two studies, the maximum expected contribution due to inter-annual variability of the mean geostrophic flow was calculated for each season. These estimates represent the surface currents; however Garrett and Petrie (1981) indicate that vertical density stratification typically observed in the Strait is associated with a reduction in mean geostrophic current speed between surface and bottom of about 0.25 ms^{-1}. The values for the mid-depth level were determined by interpolation between surface and bottom values.

The mean expected current due the geostrophic flow was calculated from the mean values for each season from the 8 years of data available. In this case the mean contributions to the flow were considered homogeneous for the whole water column.

The most significant source of uncertainty for these estimates arises from the process of geostrophic leveling of the tide gauges. By comparing the mean flow estimates given by Garrett and Petrie (1981) and Petrie et al. (1988), using two different sets of tide gauges, the corresponding error of these estimates was found to be 0.4 $ms^{-1}$for the maximum current contribution. For the values of the mean flow, an additional uncertainty of 0.5 ms^{-1} was determined, based on the range of mean values observed within the multi-year dataset.

3.0 Current statistics and discussion

3.1. Current statistics

The contributions from all three processes described in the previous section were added to produce the mean and maximum expected current estimates for each season and each depth (Table 3.1). The estimates from the individual processes (tidal, non-tidal, mean circulation with inter-annual variability) are presented separately in the Appendix following this section.

There were some differences found in most of the estimates from the north, center and south of the Strait, with the highest estimates being found in the north, and the lowest in the south section of the Strait, near the Newfoundland coast. However, the differences were small and within the bounds of statistical error of the estimates, therefore the estimates from the north section of the Strait were considered to be representative of all locations across the Strait. This finding is supported by Garrett and Petrie (1981), who found that on average the current magnitude was uniform across the Strait, except for local variations near the coastal boundaries.

Maximum Expected Current Speed [ms^{-1}] per Season and Depth				
$\Delta U = \pm 0.8$ ms^{-1}	WINTER	SPRING	SUMMER	FALL
Near Surface	3.3	3.6	4.2	4.3
Mid-Depth	3.5	3.6	4.0	3.5
Near Bottom	3.3	3.3	2.8	3.0

Table 3.1 Estimated maximum current speeds for the four seasons, at three depth levels.

Mean Expected Current Speed [ms^{-1}] per Season and Depth				
$\Delta U = \pm 1.3$ ms^{-1}	WINTER	SPRING	SUMMER	FALL
Near Surface	1.3 (1.9)	1.2 (1.8)	1.1 (1.7)	1.3 (1.9)
Mid-Depth	1.4 (1.9)	1.2 (1.7)	1.0 (1.5)	1.3 (1.8)
Near Bottom	1.4 (2.0)	1.1 (1.7)	0.8 (1.4)	1.1 (1.7)

Table 3.2 Estimated mean current speeds for the four seasons, at three depth levels. The number at the center of the columns is the sum of the mean speed of the currents from tides, atmospheric forcing and general circulation. The second number in parenthesis is the mean current speed at the time of the peak of the tide (typically 4 times a day).

It is apparent from the seasonal and depth distribution of current speeds in Table 3.1 that the bottom currents are strongest in the winter and spring season, reaching a maximum of 3.3 ms^{-1}, while the minimum of 2.8 ms^{-1} occurs in the summer. In contrast, the maximum values at mid-depth of 4.0 ms^{-1} are expected in the summer, with the lowest seasonal values of 3.5 ms^{-1} are expected in the fall and winter. The maximum expected current speed of 4.3 near the surface is expected in the fall, while the lowest surface value of 3.3 ms^{-1} is expected in the winter. The expected mean values presented in Table 3.2 follow a similar trend: the mean bottom currents are strongest in the winter season at 1.4 ms^{-1}, while the lowest mean bottom currents are expected in the summer at 0.8 ms^{-1}. The contrast between surface and bottom currents is not as pronounced for the mean values as it is for the maximum expected values. Nevertheless, the highest mean currents at the surface and mid-depth levels are in the winter and fall, while the spring and summer values are slightly lower. The combined error of these estimates considering the three different contributing processes is 0.8 ms^{-1} for the maximum expected currents, and 1.3 ms^{-1} for the mean expected currents.

The estimates for the mean and maximum expected current speeds are significantly higher than those from the field measurements, presented in Tables 2.1 and 2.2. This is not unexpected, as Petrie et al. (1988) found that the years 1963 and 1980, during which a vast majority of the measurements were conducted, were years during which the contributions from the interannual variability of the general circulation were below average. Thus, when all the processes contributing to the flow are considered, in an average year the flow is expected to be higher, as reflected in the results in Tables 3.1 and 3.2.

3.2. Discussion

This section presents a qualitative description of the three components of the currents in the Strait of Belle Isle, how they combine to create conditions that can be experienced by ships and how these conditions are expected to vary on scales ranging from hours to years.

3.2.1. Tides

The astronomic tides constitute the best understood, measured and predictable component of the currents. The current measurements available in the Strait of Belle Isle are long enough for standard harmonic tidal analysis to provide robust and accurate estimates of the dominant tidal constituents. These dominant constituents are semi-diurnal (two high tides and two low tides a day) and diurnal (one low tide and one high tide a day). Combined energy of the semi-diurnal constituents is about twice that of the diurnal constituents. Semi-diurnal and diurnal constituents combine once a day in a “constructive” manner and once a day in a destructive manner: this results in two tidal cycles each day, one with a large amplitude (”constructive” combination) and one with a smaller amplitude (“destructive” combination).

With respect to the currents in the Strait, this means that the tidal currents (oriented along the Strait) change direction about every six hours (more precisely 6.5 hours). When the tidal current starts to flow, say into the Gulf of St. Lawrence at time T, it accelerates to reach peak speed into the Gulf at about T+3, then decelerates to turn around at T+6, accelerates in the opposite direction out of the Gulf to reach peak speed out of the Gulf at T+9, decelerate to turn around into the Gulf at T+12 and so on. There are two such complete cycles each day, one with stronger currents (“constructive” combination of semi-diurnal and diurnal constituents).

The presence of several semi-diurnal constituents with slightly different periods results in a modulation of the tidal amplitude over a period of 14 days: a week of large amplitude tides ("spring" tides) is followed by a week of smaller amplitude tides ("neap" tides). The alternating spring and neap tides cycles are another source of variability in the strength of the tidal currents. Spring tide peak currents are typically about twice as strong as neap tide peak currents.

It is important to note that the variability of tidal currents during the day or over the neap/spring cycle is predictable. In fact predictions of the tidal currents in the Strait along the corridor can be provided to support operations for any planned time.

Table 4.1 presents the strongest tidal peak currents, accounting for daily and neap/spring variations throughout a year. On average the strength of the tidal peak current is about 1 ms^{-1}. Table 4.4 gives the average tidal current strength: this is the average strength during a full tidal cycle, averaged between the daily large and small tide, as well as averaged over the neap/spring cycle. Values in Table 4.4 were obtained as the average current strength of 1 year of predicted tides. The average tidal current strength from table 4.4 was used to derive the estimates in Table 3.2. Because any ship working in the Strait on a given day will experience two complete tidal cycles, we added the second value in parenthesis which is based on the average strength of the tidal peak that will be experienced by the ship at some point during that day.

3.2.2. Non-tidal Components of Current Speed

The regional response to large scale atmospheric forcing results in displacement of water in or out of the Gulf of St. Lawrence through the Strait of Belle Isle. These currents vary in strength and direction on periods of about over a day to a week and are not necessarily associated with stormy conditions. Because semi-diurnal tides dominate in the Strait, there will be "constructive" and "destructive" combination of tidal and non tidal currents twice a day. So any ship working on a given day with significant contribution from non-tidal currents will experience hours of more favorable conditions than with the tides only ("destructive" combination) followed by hours of worse conditions ("constructive combination"). The non tidal currents are very difficult to predict and any operations lasting several months will experience highly variable conditions.

3.2.3. Inter-annual variability of the general circulation

The observed inter-annual variability of the general circulation has a large range and is highly unpredictable. That is why this large observed range was used in Table 4.6 and Table 3.2 as a measure of the uncertainty of the estimates, because it is not possible to predict where a given future year will fit in the range. As for the non-tidal currents, the general circulation can combine in a "constructive" or "destructive" way with tidal currents. Similarly, in the presence of significant general circulation during the season of operations, any ship working on a given day will experience hours of more favorable conditions than with the tides only followed by hours of worse conditions.

Part of the general circulation is associated with vertical and lateral variations in sea water density. These density variations result in variation in current strength across the Strait or between the surface and the bottom. When the currents associated with the general circulation are present, this horizontal or vertical shear can result in the mean currents being in opposite directions on either side of the Strait, or at the surface and the bottom. Horizontal or vertical shear of the mean current as typically observed in the Strait results in a difference of about 0.5 ms^{-1} between surface and bottom current strength. Because the mean current combines with the tidal currents, on a given day there will be periods of time when the vertical shear of the mean current results in surface and bottom currents in opposite directions and periods of time when it results in surface and bottom currents in the same direction but strengths differing by 0.5ms^{-1}. In either case, that shear will be felt by any operation involving a ship and handling of equipment at the bottom. It is important to note that although that shear is important in scientific studies that focus on large scale motion of water masses with different properties, it is of similar magnitude to the shear resulting from bottom acting on the tidal flow. Due to bottom friction, tidal currents reverse earlier near the bottom than higher up in the water column, resulting in vertical shear of tidal currents around the time of flow reversal.

4.0 Appendix

4.1. Maximum Current Conditions

Maximum Tidal Contribution to Current Speed [ms^{-1}] per Season and Depth				
$\Delta U = \pm 0.1\ ms^{-1}$	WINTER	SPRING	SUMMER	FALL
Near Surface	1.4			
Mid-Depth	1.6			
Near Bottom	1.4			

Table 4.1 Maximum tidal contribution to current speeds for every season, at three depth levels.

Maximum Non-Tidal Contribution to Current Speed [ms^{-1}] per Season and Depth				
$\Delta U = \pm 0.3\ ms^{-1}$	WINTER	SPRING	SUMMER	FALL
Near Surface	0.6	0.7	1.6	1.6
Mid-Depth	0.8	0.7	1.3	0.7
Near Bottom	0.9	0.6	0.4	0.5

Table 4.2 Maximum non-tidal contribution to current speeds for the four seasons, at three depth levels.

Maximum Inter-Annual Contribution to Current Speed [ms^{-1}] per Season and Depth				
$\Delta U = \pm 0.4\ ms^{-1}$	WINTER	SPRING	SUMMER	FALL
Near Surface	1.2	1.5	1.2	1.3
Mid-Depth	1.1	1.4	1.1	1.2
Near Bottom	0.95	1.25	0.95	1.05

Table 4.3 Maximum inter-annual variability contribution to current speeds for the four seasons, at three depth levels.

4.2. Mean Current Conditions

Mean Tidal Contribution to Current Speed [ms^{-1}] per Season and Depth				
$\Delta U = \pm 0.1\ ms^{-1}$	WINTER	SPRING	SUMMER	FALL
Near Surface	0.4			
Mid-Depth	0.5			
Near Bottom	0.4			

Table 4.4 Mean tidal contribution to current speeds for every season, at three depth levels.

Mean Non-Tidal Contribution to Current Speed [ms^{-1}] per Season and Depth				
$\Delta U = \pm 0.3\ ms^{-1}$	WINTER	SPRING	SUMMER	FALL
Near Surface	0.2	0.2	0.3	0.2
Mid-Depth	0.3	0.2	0.2	0.2
Near Bottom	0.4	0.2	0.1	0.1

Table 4.5 Mean non-tidal contribution to current speeds for the four seasons, at three depth levels.

Mean Inter-Annual Contribution to Current Speed [ms^{-1}] per Season and Depth				
$\Delta U = \pm 0.9\ ms^{-1}$	WINTER	SPRING	SUMMER	FALL
Near Surface	0.67	0.54	0.34	0.64
Mid-Depth	0.67	0.54	0.34	0.64
Near Bottom	0.67	0.54	0.34	0.64

Table 4.6 Mean inter-annual variability contribution to current speeds for the four seasons, at three depth levels.

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