Ocean Current Observations Near McMurdo Station, Antarctica from 1991 to 1993: Relation to Wastewater Discharge Dispersal

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ABSTRACT

This report analyzes current measurements from McMurdo Sound, Antarctica, in relation to dispersal of the McMurdo Station wastewater plume. Current meters (seven) were deployed near McMurdo Station, Antarctica, from December 1992 to November 1993. Analyses include (a) summaries of current speed and direction, (b) directional analyses of flow, (c) time series current vectors averaged over 1, 3, 6, 12, and 24 hours, (d) principal axes of flow, (e) maps of mean seasonal flow, (f) a local bathymetric map, (g) progressive vector plots, (h) spectral analyses, and (i) time series of daily winds at McMurdo Station. Year-long measurements indicated significant variation in flow near McMurdo Station, including strong seasonal shifts, which are likely related to changes in ice cover and wind stress and to overall dominance by diurnal tidal motions. Three distinct oceanographic seasons were apparent in the time series. The spring-summer period is dominated by regional southward flow, which generates a counter-clockwise eddy (McMurdo gyre) adjacent to McMurdo Station. During summer to fall, low regional ice cover appears related to a current pattern of alternating northward and southward flow. In fall and winter, northward flow dominates all stations. A recommendation is made to reposition the outfall pipe offshore of the McMurdo gyre.

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Ocean Current Observations near McMurdo Station, Antarctica from 1991 to 1993: Relation to Wastewater Discharge Dispersal

1. INTRODUCTION

Analyses of ocean currents in the vicinity of McMurdo Station, Antarctica, are relevant to the transport and dispersal of wastewater from the McMurdo Station sewage outfall pipe. Observations of ocean currents during the initial phases of this study have been presented by Howington et al. (1992), McFeters (1993), and McFeters et al. (1993). These studies, using coliform bacterial counts as an indicator of dispersion of the wastewater plume and current meters to measure flow patterns, indicated that dispersal of the plume by local currents does not effectively remove the plume from the vicinity of McMurdo Sound, under the present outfall pipe location. Moreover, these studies suggest that, although the flow pattern is generally consistent with transport of the plume away from McMurdo Station, episodes of current reversal are sufficient to transport the wastewater plume along the shore toward the southeast, eventually overlapping the seawater intake area near the McMurdo jetty. Several concerns included (a) impacts of wastewater inputs to nearshore benthic and pelagic habitats adjacent to McMurdo Station (heavily utilized sites for basic scientific research), (b) effects of wastewater input to the McMurdo Station fresh water intake source, and (c) reduction in human impacts on the McMurdo Sound ecosystem. These concerns motivated studies to characterize nearshore currents more extensively in relation to dispersal of the wastewater plume. This report discusses analysis results of current observations from November 1992 to November 1993, in addition to all current measurements in the McMurdo Station vicinity from 1991 through 1993.

Ocean currents are generated from a variety of sources including wind stress, planetary motions that induce gravitational tides and tidal currents, density gradients, flexure of ice shelves, and other sources, all of which are superimposed to produce the flow field detected by current sensors. Observations of currents are often divided into periodic and aperiodic (or net) motions to dissect at least some potential factors regulating the flow field. Periodic motions are currents that vary in speed or direction or both, over specific periods associated most often with known planetary motions (e.g., diurnal or semidiurnal tidal motions). Aperiodic flow is the residual (or net) motion remaining after the periodic oscillatory flow is filtered from current patterns. Aperiodic motions may consist of actual net transport arising from various sources, but may also be related to unidentified periodic motion. For example, observations over a 3-month period are not sufficient to detect period patterns of flow with cycles greater than 3 months. Thus, long-period cycles (more than 3 months) would be measured as net aperiodic flow. Any record of current observations includes both aperiodic and periodic motions superimposed upon one another. Periodic motions are detected using spectral analyses to identify the dominant frequencies discernable in any set of current observations. Data filters are then used to filter out periodic motions so that aperiodic (or net) motions can be assessed. Net motion is also evident from overall averages of flow over the observation period.

Flow patterns near McMurdo Station should be first placed in the context of the larger scale currents, which must have profound effects on small-scale features of concern in this study.

Though few regional studies of currents are available for the southwest Ross Sea, calculations of geostrophic flow from hydrographic data and limited current measurements have been used to generate a synoptic characterization of flow in this region. Generally, a clockwise gyre prevails in the Ross Sea, with a westward-flowing quadrant found in the southern Ross Sea (Figure 1). This gyral flow likely contributes to the prevailing westward flow observed along the Ross Shelf Barrier edge. Westward coastal flow may be enhanced by wind-driven Ekman transport driven by northward katabatic atmospheric flow off the Antarctic continent in the western Ross Ice Shelf region.^a Ultimately, this coastal current flows toward Ross Island along the Ross Shelf Barrier, and turns south as it flows westward around Cape Bird, but also may flow around the southern boundary of Ross Island under the Ross Ice Shelf, only to emerge in southern McMurdo Sound as a northward-flowing current. The relative dominance of southward flow from the Cape Bird region, or northward flow from under the Ross Ice Shelf may depend upon presently unknown factors. Hypotheses to explain interannual variation in flow observed directly^b (Dunbar and Leventer, 1993) and indirectly (Barry, 1988; Barry and Dayton, 1988; Dayton, 1989) include variation in zonal winds (e.g., El Niño southern oscillation events) and variation in ice cover extent, which may regulate wind-driven current transport. Superimposed on these factors, ventilation of the cavity under the Ross Ice Shelf appears to result in a net transport from the central shelf cavity region to the northwest in the vicinity of Ross Island, based upon the salinity signature of waters in the region (Jacobs et al., 1985; Pillsbury and Jacobs, 1985). Thus, a variety of large-scale (perhaps even global-scale) processes may influence current patterns near McMurdo Station.

Ocean currents in McMurdo Sound, Antarctica, have been investigated by several researchers from 1907 to the present, with most observations made very near McMurdo Station. Early current observations in McMurdo Sound were made over very short periods (hours to days) and indicated that currents varied in both magnitude and direction near McMurdo Station (Gilmor et al., 1960 and 1962; Hodgson, 1907). Other studies suggested seasonal shifts in flow (Littlepage, 1965; Tressler and Ommundsen, 1962), in addition to shorter term periodic motions. More recent studies, including data collected over periods up to 2 months during the austral spring^c (Barry and Dayton, 1988; Barry et al., 1990; Heath, 1971 and 1977; Lewis and Perkin, 1985), indicate that flow adjacent to McMurdo Station is dominated by diurnal periodic motion. Heath (1977) and Barry and Dayton (1988) showed that oscillations in flow speed and direction were associated mainly with diurnal tidal constituents related to specific planetary motions. The dominant constituents were the principal lunar diurnal (O1), principal solar diurnal (K1), and luni-solar diurnal (P1) constituents with periods of 25.82, 24.07, and 23.93 hours, respectively. Semidiurnal components (M2, K2, S2, N2) were of secondary importance in McMurdo Sound. Tidally induced flow in McMurdo Sound is thought to be generated directly by equilibrium tidal

a. Bromwich, D. H., J. F. Carrasco, Z. Liu, and R. Tzeng, 1993, "Hemispheric Stmospheric Bariations and Oceanographic Impacts Associated with Katabatic Surges across the Ross Ice Shelf, Antarctica," *Journal of Geophysical Research - Atmospheres*, in press.

b. Dunbar, R. B., J. P. Barry, A. Leventer, and W. Testa, "Year-long Current Observations from McMurdo Sound During 1989 to 1993," manuscript in preparation.

c. Raytheon Service Company, 1983, "Report on the McMurdo Station Water Quality Study", Unpubl. Rep ITT Antarctic Serv.

Figure 1

Figure 1 Map of Ross Sea Region, showing large scale current pattern

motions and perhaps by tidally induced flexing of the Ross Ice Shelf (Doake, 1978; Holdsworth, 1977; MacAyeal, 1984), which may accentuate or damp local currents.

Measurements of net transport (aperiodic flow) throughout McMurdo Sound are somewhat complex, with southward transport in the eastern Sound, particularly in deeper waters, and northward in the western Sound (Barry and Dayton, 1988) (Figure 2). Flow in shallow waters (c. 100 m) of the eastern Sound was more variable in both speed and direction than that observed in deeper water (c. 500 m). Coastal topography is also important to flow, particularly near McMurdo Station. During periods of consistent southward flow, Hut Point may interrupt the flow field and modify flow speed and direction, particularly downstream of the flow, producing a counter-clockwise eddy positioned adjacent to McMurdo Station. Short-term studies performed during the late 1970s to early 1980s^d included current measurements for five stations in this area and suggested that a counter-clockwise gyre was positioned south of Hut Point, approximately directly offshore of the present outfall site. If this gyre is temporally persistent, it may transport the wastewater plume effectively from the outfall pipe and away from McMurdo Station. However, decay of the gyre, as suggested by McFeters et al. (1993) may be responsible for episodes of wastewater retention near McMurdo Station.

Optimal design and positioning of the wastewater outfall pipe is contingent upon knowledge of the average flow field in the vicinity of the plume during wastewater plume dilution and dispersal. In addition, information concerning the magnitude and pattern of variation in the flow field, and their effect on plume dispersal, are of interest. Thus, it is desirable to identify the existence, position, extent, and persistence of the gyre adjacent to McMurdo Station (McMurdo gyre). The optimal position for relocation of the McMurdo Wastewater Outfall pipe is likely within or beyond the outer quadrant of this gyre. Thus, the wastewater plume would be carried in the prevailing regional mainstream current (on a spatial scale incorporating the Ross Island coast, rather than simply the McMurdo Station vicinity. When the McMurdo gyre is present, the plume would be swept away from McMurdo Station toward the south. The direction and distance of plume transport during periods when the McMurdo gyre has decayed are less predictable, but early results (Howington et al., 1992; McFeters et al., 1993) suggest that the plume will continue toward the south, at least during summer, when southward regional flow prevails.

In this study, results are presented of current observations collected over a 1-year period, extending considerably the length of current observations near McMurdo Station. Moreover, these results include periods of observation beyond spring, including all seasons, both with and without significant ice coverage. Also included are details of all current observations collected during this project and a synoptic summary of the flow field in the McMurdo Station vicinity, based on a compilation of all available current records. Comparisons of local currents with local wind data (McMurdo Station Weather Office) are also provided. Recommendations for outfall pipe relocation are discussed in relation to results of current observations.

d. Raytheon Service Company, 1983, "Report on the McMurdo Station Water Quality Study", Unpubl. Rep ITT Antarctic Serv.

Figure 2

Figure 2 Map of McMurdo Sound, indicating regional flow pattern. Dashed line indicates approximate position of fast ice edge during October.

2. METHODS

2.1 Current Meter Placement and Deployment

2.1.1 1991–1992 Spring-Summer Current Observations

Current meters (InterOcean Model S4) were deployed during the austral spring for periods of 1 to 3 months at various locations (Stations A to M) adjacent to McMurdo Station (Figure 3), to characterize the pattern and variation of the flow field impacting the wastewater plume from the McMurdo Station wastewater outfall. These studies were performed in conjunction with a sampling program to determine concentrations of fecal coliform bacteria in surface waters and sea ice in this area (Howington et al., 1992; McFeters et al., 1993). Current stations were located throughout the area identified as a gyre by Raytheon Service Company,^e and also included sites adjacent to Hut Point, assumed to be indicative of prevailing regional flow patterns. Current meters were suspended from the sea ice and deployed through access holes 48 in. in diameter drilled through the sea ice (Figure 4). Meters were positioned approximately 30 to 50 ft above the sea floor, depending upon water depth. Current measurements were programmed on each meter to calculate the mean flow direction and speed over a 5-minute period and record each 5-minute average. Intervals between 5-minute averages ranged from continuous (one average each 5-minute interval) to 1 hour (one 5-minute average per hour), and depended upon current meter memory and deployment duration. Deployment dates, grid locations (McMurdo ASA location grid), station characteristics, and sampling specifications are listed in Table 1. Results of these initial studies confirmed the presence and approximate position of the McMurdo gyre and of temporal scales of persistence of the gyre.

2.1.2 1992–1993 Year-Round Current Meter Deployment

Seven current meters were deployed for a 1-year period (December 1992 to November 1993) to identify spatial and temporal characteristics of the McMurdo gyre, particularly with respect to transport and dispersal of the wastewater plume. Station locations were established based upon results from spring-summer observations during 1991–1992. Specifically, station configuration was planned to bracket the McMurdo gyre and to identify the transition zone between the inner quadrant (northwestward coastal flow) and outer quadrant (mainstream southward flow) of the gyre. Station S, the most southerly station, was positioned in an area thought to be near the southern extent of the gyre. Additional stations were planned for Hut Point and other sites along a transect crossing the gyre from the present outfall to the SW outside the gyre to identify and characterize the prevailing mainstream flow patterns. Unfortunately, several current meters were inadvertently positioned incorrectly at sites with sub-optimal value for the planned gyre characterization. Current measurement schedules were programmed on each meter to calculate the mean flow direction and speed over a 2-minute period and record one 2-minute average every 15 minutes. Current meters (InterOcean model S4) deployed through access holes were anchored by steel weights at the bottom of the array and buoyed by a benthos 16-in. glass-sphere float at the top (Figure 4). Meters were positioned to be approximately midway between the surface and

e. Raytheon Service Company, 1983, "Report on the McMurdo Station Water Quality Study", Unpubl. Rep ITT Antarctic Serv.

Table 1

List of station characteristics, grid coordinates, deployment dates and sample specifications for current meter observations in McMurdo Sound during 1991 to 1993. NS Grid and EW Grid are McMurdo Local Grid Coordinates (feet). Period is the duration of current observations (days). Cycle time is cycle period for the current meter observations, in minutes. Average is the number of minutes of per current average within each cycle time. N is the total number of averages (current vectors) recorded during the observation period.

STATION	NS GRID	EW GRID	START DATE	START TIME	PERIOD	CYCLE	AVERAGE	N
A	10088	1694	15 Oct 91	1600	75.9	5	5	21883
A	10088	1694	15 Nov 92	1033	8.9	15	5	855
B	9945	2392	4 Dec 91	902	11.2	5	5	3215
C	9828	3116	24 Nov 91	2045	9.5	5	5	2741
D	9503	3287	20 Oct 91	1121	42.7	5	5	12292
D	9503	3287	8 Sep 92	1515	57.8	60	5	1388
E	9304	3143	20 Oct 91	1115	70.1	5	5	20193
E	9304	3143	8 Sep 92	1515	57.8	60	5	1388
E	9304	3143	6 Nov 92	1323	8.0	5	5	2303
F	8987	3723	23 Oct 91	1159	12.1	5	5	3482
G	8337	4064	5 Nov 91	1202	9.2	5	5	2652
H	7746	4043	15 Nov 91	1115	9.3	5	5	2664
I	9319	1650	6 Nov 92	1455	7.9	5	5	2282
J	8959	2571	6 Nov 92	1401	8.0	5	5	2294
J	8959	2571	16 Nov 92	1033	8.9	15	5	851
K	8758	2261	16 Nov 92	1018	8.9	15	5	856
L	8525	1923	16 Nov 92	1026	8.9	15	5	856
M	8787	3579	6 Nov 92	1505	8.0	5	5	2290
N	9460	3176	3 Dec 92	1233	341.9	15	2	32825
O	9481	2454	3 Dec 92	1427	341.3	15	2	32762
P	9479	1647	3 Dec 92	1550	342.3	15	2	32858
Q(t)	9620	1190	3 Dec 92	1737	348.1	15	2	33418
Q(b)	9620	1190	3 Dec 92	1741	348.1	15	2	33421
R	9988	1523	3 Dec 92	1645	348.1	15	2	33416
S	8416	3311	3 Dec 92	1035	346.3	15	2	33246

Figure 3 **Map of McMurdo Sound showing locations of current meter stations for observations. Letters indicate locations of current meter stations from 1991 to 1993.**

Figure 3

E/W Grid Loc. (J.S. Grid: ft)

Figure 4. Design of current meter moorings. A. Summer deployment anchored to sea ice. b. Winter deployment anchored to sea floor.

sea floor. Station locations were surveyed by ASA personnel (Jeff Scanniello) and located on the McMurdo local grid map. Meters were recovered during November 1993 by divers (J.P. Barry and G.H. Dayton), after relocating station sites by surveying (J. Scanniello: ASA) and acoustic search methods. Acoustic searches were performed using a Furuno echo sounder, for meters (Stations Q and S) located 50 m or more from recorded grid locations. Divers attached recovery lines, and meters were pulled to the surface using a tracked vehicle (Spryte) and pulley system. Stations Q and S were resurveyed following current meter recovery.

2.2 Bathymetry of the McMurdo Station Coast

Water depth was determined at many sites to enable creation of a bathymetric chart of the nearshore region adjacent to McMurdo Station. Bottom depth was measured to the nearest meter with a Furuno depth sounder (ASA- Cray Science Facility), or with a weight and line for most Winter Quarters Bay stations. Each site was surveyed (ASA surveyor) to provide McMurdo ASA location grid coordinates or McFeters (T-325) grid coordinates (converted to McMurdo ASA location grid coordinates). Grid coordinates and depths, along with a compilation of grid coordinates for the McMurdo coastline (digitized from an aerial photograph by Barry and Dayton) were contoured using Deltagraph 3.0.

2.3 Data Processing

Upon recovery of current meters, data were downloaded to disk storage as soon as possible. General flow characteristics were inspected using InterOcean S4 application software to assess current data for obvious sensor failure or error. Binary files were then converted to ASCII files and processed by a FORTRAN program (J. Barry) used to average the data over specified intervals (1, 3, 6, 12, and 24-hour periods).

2.4 General Flow Characteristics near McMurdo Station

Overall, mean flow direction and speed for each station were calculated as the average of all 3-hour vector averages, corrected for compass variation. Similarly, seasonal averages were calculated for three oceanographic seasons, including spring-summer (December through January), summer-fall (February through May), and fall-winter (June through September). Stations near Hut Point (Stations P, Q, R) were assumed to be most representative of the mainstream or regional flow field in the vicinity of McMurdo Station. Time series of current vectors were calculated from raw data (2-minute averages every 15 minutes) using 1, 3, 6, 12, and 24-hour averages.

2.5 Principal Axes of Flow

Principal axes of flow were estimated from 3-hour current vector averages by identifying the compass axis containing the maximum mean absolute flow speed for each station. The frequency of 3-hour average current vector observations along each 30-degree compass interval were summed to identify the percentage of flow in each compass interval. Similarly, the mean speed of flow was calculated for each compass interval by averaging the speeds of all 3-hour average current vectors occurring in each 30-degree compass interval. The percentage of the total

transport towards each 30-degree heading interval was calculated as the product of the proportion of flow and the mean flow speed, for each compass interval.

2.6 Periodic Characteristics of McMurdo Sound Currents

Current vectors averaged over 1 hour were separated into north-south and east-west components and analyzed using spectral analyses for the dominant frequencies of flow. Analyses consisted of a fast fourier transform (Matlab), using a data string length of 2,048, a Hanning window, and an overlap of 1,024. Power spectra for each flow component at each station were standardized to a maximum of 1.0 and were plotted versus frequency (cycles per hour) to illustrate the dominant frequencies of the flow field for each data string.

2.7 Aperiodic Characteristics of McMurdo Sound Currents

Net current speeds and directions were calculated for the entire data record from each station and within three oceanographic seasons (defined above). Current vectors (3-hour means) were separated into north-south and east-west components and averaged over total or seasonal intervals. Progressive vector plots were prepared using cumulative north-south and east-west components of flow through the observation period.

2.8 Correlation of Flow Among Stations

Correlations among north-south and east-west components of flow within and among stations were calculated from time series of 3-hour average east-west and north-south current vectors for each station. Correlations were calculated for all overlapping data for each comparison. Additional analyses were performed among all stations and vector components for flow divided into time periods when flow at Hut Point (mainstream flow: estimated from Station Q (top)) was southward or northward. Thus, correlation among stations were made during periods of regional southward flow, northward flow, and overall annual flow.

2.9 Low-pass Filtering of Current Records

East-west and north-south components of flow (1-hour averages) were low-pass filtered to remove tidal variations on frequencies of 30 hours or less. Filtered time series were plotted with unfiltered data to enable comparisons of tidal motion with aperiodic or low frequency motions, which may affect transport of the wastewater plume.

3. RESULTS

3.1 Deployment Information

Seven current meters were deployed at six stations (N, O, P, Q, R, S) in McMurdo Sound, adjacent to McMurdo Station (Figure 3). These meters collected current observations continuously for nearly 1 year from early December 1992 to mid-November 1993. All seven current meters functioned properly throughout the deployment period. Details of the deployment schedule are presented in Table 1.

3.2 McMurdo Area Bathymetry

A bathymetric contour map of the vicinity of McMurdo Station is presented in Figure 5. Each red dot denotes a position of known depth. Together, these points were used to create the contours shown. The bottom slopes rapidly to deep water off McMurdo, particularly near Hut Point. There is a sill in Winter Quarters Bay, and a small basin near 30 m in depth in the upper area of the bay.

3.3 Regional Scale Pattern of Flow near McMurdo Station

As discussed in the Introduction, local variation in currents are allied quite strongly to regional processes (i.e., southeast McMurdo Sound) and larger scale processes (i.e., southwest Ross Sea). Changes on even global scales may be manifested as variation in currents adjacent to McMurdo Station. Thus, it is important to first consider regional patterns of flow during 1993, and evaluate local patterns with respect to regional flow.

Flow adjacent to the western and southwestern shores of Ross Island, and particularly flow in the vicinity of the Hut Point Peninsula, can be considered the mainstream flow near McMurdo Station, which is modified by local topography (e.g., Hut Point) to generate local patterns of flow. During spring and early summer, regional flow, identified in other studies (e.g., Barry and Dayton, 1988) and corroborated by data reported here, includes fairly consistent southward transport in eastern McMurdo Sound, flowing generally southward past Hut Point. The local flow pattern arises largely from the effects of coastline configuration and local bathymetry. The projection of Hut Point into southward flow along the Hut Point Peninsula creates a downstream eddy, positioned adjacent to McMurdo Station, that may persist as long as the regional southward flow. Regional currents, however, vary over several temporal scales (see below) and thus have important consequences for local flow. Even during spring and summer, when southward regional flow is most consistent, it pulses with the daily tide and occasionally reverses in direction towards the north for short periods (hours). As discussed below, during other seasons, regional currents are even more temporally variable or generally northward (winter). During periods of northward regional flow, local currents, such as the gyre south of Hut Point, may be dramatically different than when southward regional flow dominates. For example, the counter-clockwise gyre adjacent to McMurdo Station was absent during winter when the regional current was predominantly northward. During this time, a clockwise gyre may have formed north of Hut Point, though no data are available to assess this concept.

Figure 5 Bathymetry of McMurdo Sound in the vicinity of McMurdo Station, Antarctica.
Red dots indicate locations of known depth. Contours on 10 m intervals.

Figure 5

E/W Grid Loc. (J.S. Grid: ft)

Figure 6 Overall net flow for all current observations at stations near McMurdo Station from 1991 to 1993, superimposed on a map of McMurdo bathymetry. Red dots indicate locations of Stations. Current vectors (yellow) indicate the direction and speed of flow for the entire observation period for each station. Scale bar at bottom. Current vectors are for different lengths of observations among stations. Note the general counter-clockwise gyre formed by all vectors.

Figure 6

E/W Grid Loc. (J.S. Grid: ft)

For this study, regional flow can be estimated only from current meters at stations least affected by shoreline topography. Thus, stations offshore from Hut Point (P, Q, R), even though they are still quite close to Hut Point (c. 100-300 m) are most representative of regional flow. The major effects of Hut Point on current stations P, Q, and R probably include intensification of current speed owing to compression of along-shore flow as it approaches Hut Point from the north or south, and slight deflection of flow in an along-shore direction. Current patterns at stations (N, O, S) nearer shore and within the McMurdo bight (i.e., within a line from Hut Point to the McMurdo jetty), are more representative of local-scale circulation.

3.4 General Pattern of McMurdo Station Currents

Year-long observations of currents in McMurdo Sound revealed considerable variation in the direction and magnitude of flow adjacent to McMurdo Station over both temporal and spatial scales. An overall average of all current records for year-long stations (this study) and shorter term spring and summer observations (data from 1991-1992) provide a composite view of flow near McMurdo Station (Figure 6), in which the counter-clockwise flow of the McMurdo gyre is evident. Station A, at Hut Point, differs from Stations P, Q, and R, owing to the year-long observations at the latter stations and spring observations at the former. Mean overall current speeds for all stations are presented in Table 2.

Large seasonal variation in surface flow may be related to the effects of ice cover and local winds. The regional pattern of flow near McMurdo Station, estimated from current meters near Hut Point, was generally southward during spring and summer (i.e., October through January), similar to current records from 1991 and 1992, and other studies (see the Introduction). Figure 7 illustrates the pattern of flow at all stations occupied in this period from 1991 to 1993. Table 3 lists the means speeds and directions of flow at each station during three seasonal periods. During spring and summer, a counter-clockwise flowing eddy positioned south of Hut Point (hereafter termed McMurdo gyre) was generally well-developed, though there were episodes of decay when this eddy was not evident. In late summer and fall (February through May), the regional flow was more oscillatory in direction with lower net southward transport (Figure 8). During late fall and winter (June through September) the regional pattern included strong northward flow, especially early in this period. Figure 9 shows this strong northward flow, particularly for stations near Hut Point. Although southward flow at Station A near Hut Point appears to oppose northward flow at other nearby stations (P, Q, R) for the same season, data from Station A were collected in September 1992, while data for Stations P, Q, and R are from June through September 1993. The greater northward flow at Station Q is the shallower meter at this site.

Local-scale currents inside Hut Point near Winter Quarters Bay and the present outfall site (Stations N, O, S) were generally oriented along the shore, but flowed northward during most of the year, and probably transported the wastewater plume toward Hut Point much of the time. The direction and magnitude of flow at these sites appears strongly linked to flow at outer stations. Southward regional flow (outer stations) promotes development of the McMurdo gyre, with fairly strong northwestward flow at the inshore stations. North to northwestward flow at the outer stations is paralleled by similar directional flow inshore. Induction of the McMurdo gyre by Hut Point did not appear to occur during periods of northward regional flow. Instead, a clockwise eddy may be present north of Hut Point. Occasional shifts in flow direction and speed were evident for inshore stations, however, and are very important in the local dispersal of the

Table 2 Flow characteristics for current observation stations occupied during 1991 to 1993, based on 3h average data. Overall net and absolute current speeds for east-west (EW) and north-south (NS) components of flow are listed with standard deviations (St. Dev.), mean net speed, heading (angle), and sample size (N). File lists the data code for each station as station-year-data series number. Eastward and northward net flow are positive values. Westward and southward net flow are negative. Absolute speeds represent the average current speed along EW and NS axes. Averages are derived from 3 h EW and NS current vectors averages. Z(bot.) is bottom depth for each station in meters. Z(CM) is depth of the current meter (m).

STATION	FILE	Z (BOT.)	Z (CM)	NET SPEED				SPEED ANGLE		ABSOLUTE SPEED				N
				EW	St. Dev.	NS	St. Dev.			EW	St. Dev.	NS	St. Dev.	
A	A-91-1	22	11	1.72	2.82	-9.66	11.23	9.8	170	2.29	2.38	10.14	10.80	607
A	A-92-1	22	11	0.04	1.51	-6.85	9.68	6.8	180	1.13	1.00	7.39	9.27	71
B	B-91-1	27	14	-0.64	2.00	-0.06	1.40	0.6	264	1.63	1.31	1.11	0.86	89
C	C-91-1	22	11	-0.24	0.57	-0.57	0.90	0.6	202	0.49	0.38	0.83	0.67	76
D	D-91-1	15	7	-1.23	2.62	-0.26	1.97	1.3	258	2.11	1.97	1.45	1.36	341
D	D-92-1	15	7	-0.86	2.14	0.89	2.22	1.2	316	1.81	1.44	1.89	1.46	462
E	E-91-1	27	14	-2.14	2.40	1.35	2.34	2.5	302	2.49	2.03	2.13	1.65	560
E	E-92-1	27	14	-1.26	2.50	1.20	2.61	1.7	314	2.23	1.69	2.35	1.65	462
E	E-92-2	27	14	-2.32	2.90	2.25	2.34	3.2	314	3.05	2.10	2.75	1.70	63
F	F-91-1	7	3	1.14	0.93	-0.27	1.34	1.2	103	1.34	0.61	1.08	0.84	96
G	G-91-1	12	6	-0.11	1.27	-0.04	4.04	0.1	252	0.88	0.92	3.39	2.15	73
H	H-91-1	38	19	-0.44	1.58	-0.95	3.09	1.0	205	1.29	0.99	2.68	1.79	74
I	I-92-1	51	26	-1.57	6.09	-3.01	9.61	3.4	207	5.17	3.52	7.37	6.81	63
J	J-92-1	58	29	-1.98	3.55	1.68	2.63	2.6	310	3.55	1.93	2.59	1.73	63
J	J-92-2	58	29	-2.12	3.31	1.64	2.26	2.7	308	3.22	2.24	2.19	1.73	70
K	K-92-1	69	34	-0.91	3.66	0.25	3.69	0.9	285	3.12	2.08	3.00	2.14	71
L	L-92-1	65	32	1.13	5.33	-2.48	8.10	2.7	156	3.76	3.92	5.61	6.32	71
M	M-92-1	27	14	-1.31	3.15	2.18	3.35	2.5	329	2.50	2.30	3.10	2.51	63
N	N-93-1	22	15	-1.54	2.82	1.09	2.40	1.9	305	2.39	2.15	1.96	1.76	2770
O	O-93-1	33	19	-2.29	4.41	1.25	2.05	2.6	299	3.91	3.07	1.72	1.68	2735
P	P-93-1	47	25	-1.78	10.82	-1.91	13.99	2.6	223	8.60	6.80	10.26	9.70	2738
Q	Q-93-1(b)	65	42	-1.47	9.43	-1.88	13.68	2.4	218	7.22	6.24	10.67	8.76	2785
Q	Q-93-2(t)	65	22	-0.50	8.82	0.24	14.66	0.6	296	6.97	5.42	11.22	9.43	2784
R	R-93-1	39	27	-2.57	8.30	-2.54	14.46	3.6	225	6.21	6.09	11.02	9.70	2784
S	S-93-1	48	25	-0.48	2.90	2.60	3.96	2.6	350	2.13	2.03	3.72	2.94	2770

Figure 7 Net flow at all current observation stations occupied during the spring to summer season (October through January). Symbols as in Figure 6.

Figure 7

E/W Grid Loc. (J.S. Grid: ft)

Table 3. Seasonal patterns of flow for Stations in McMurdo Sound. Three hour mean vectors were averaged within specific seasons (listed). Net flow, standard deviation, and sample size (N) are listed for EW and NS flow, for all available data at each station.

STATION	SEASON	MONTHS	EW SPEED		NS SPEED		OVERALL		N
			cm/s	St. Dev.	cm/s	St. Dev.	Angle	cm/s	
A	Sp-Sum	ONDJ	1.55	2.76	-9.36	11.10	171	9.49	678
	Sum-Fal	FMAM							
	Fal-Win	JJAS	0.03	1.34	-7.04	9.70	180	7.04	69
B	Sp-Sum	ONDJ	-0.64	2.00	-0.06	1.40	264	0.64	89
	Sum-Fal	FMAM							
	Fal-Win	JJAS							
C	Sp-Sum	ONDJ	-0.24	0.57	-0.57	0.90	202	0.62	76
	Sum-Fal	FMAM							
	Fal-Win	JJAS							
D	Sp-Sum	ONDJ	-1.05	2.40	0.27	2.17	285	1.09	632
	Sum-Fal	FMAM							
	Fal-Win	JJAS	-0.89	2.21	0.86	2.20	314	1.24	171
E	Sp-Sum	ONDJ	-1.86	2.51	1.51	2.38	309	2.40	914
	Sum-Fal	FMAM							
	Fal-Win	JJAS	-1.29	2.45	0.45	2.74	289	1.37	171
F	Sp-Sum	ONDJ	1.14	0.93	-0.27	1.34	103	1.17	96
	Sum-Fal	FMAM							
	Fal-Win	JJAS							
G	Sp-Sum	ONDJ	-0.11	1.27	-0.04	4.04	252	0.12	73
	Sum-Fal	FMAM							
	Fal-Win	JJAS							
H	Sp-Sum	ONDJ	-0.44	1.58	-0.95	3.09	205	1.05	74
	Sum-Fal	FMAM							
	Fal-Win	JJAS							
I	Sp-Sum	ONDJ	-1.57	6.09	-3.01	9.61	207	3.40	63
	Sum-Fal	FMAM							
	Fal-Win	JJAS							
J	Sp-Sum	ONDJ	-2.05	3.41	1.66	2.43	309	2.64	133
	Sum-Fal	FMAM							
	Fal-Win	JJAS							
K	Sp-Sum	ONDJ	-0.91	3.66	0.25	3.69	285	0.95	71
	Sum-Fal	FMAM							
	Fal-Win	JJAS							
L	Sp-Sum	ONDJ	1.13	5.33	-2.48	8.10	156	2.72	71
	Sum-Fal	FMAM							
	Fal-Win	JJAS							
M	Sp-Sum	ONDJ	-1.31	3.15	2.18	3.35	329	2.54	63
	Sum-Fal	FMAM							
	Fal-Win	JJAS							
N	Sp-Sum	ONDJ	-1.20	2.29	1.26	2.50	316	1.74	825
	Sum-Fal	FMAM	-2.10	3.22	1.34	2.48	303	2.49	960
	Fal-Win	JJAS	-1.29	2.73	0.71	2.17	299	1.47	985

Table 3 (continued)

STATION	SEASON	MONTHS	EW SPEED		NS SPEED		OVERALL		N
			cm/s	St. Dev.	cm/s	St. Dev.	Angle	cm/s	
O	Sp-Sum	ONDJ	-2.89	3.28	0.82	1.64	286	3.01	790
	Sum-Fal	FMAM	-1.92	4.47	1.19	1.70	302	2.26	960
	Fal-Win	JJAS	-2.18	5.04	1.65	2.53	307	2.73	985
P	Sp-Sum	ONDJ	2.68	10.87	-10.88	15.73	166	11.21	801
	Sum-Fal	FMAM	-1.54	9.04	-0.98	10.48	238	1.82	952
	Fal-Win	JJAS	-5.65	10.92	4.50	11.39	308	7.22	985
Q(top)	Sp-Sum	ONDJ	3.20	9.03	-9.15	14.66	161	9.70	840
	Sum-Fal	FMAM	-0.30	7.10	0.42	11.33	324	0.51	960
	Fal-Win	JJAS	-3.85	8.86	8.08	12.75	335	8.95	985
Q(bot)	Sp-Sum	ONDJ	2.54	8.74	-9.75	13.82	165	10.08	840
	Sum-Fal	FMAM	-0.46	7.23	-1.91	10.89	194	1.97	960
	Fal-Win	JJAS	-5.88	10.07	4.88	12.35	310	7.64	985
R	Sp-Sum	ONDJ	1.97	5.75	-11.91	14.34	171	12.07	840
	Sum-Fal	FMAM	-3.07	7.05	-1.21	11.94	249	3.30	960
	Fal-Win	JJAS	-5.96	9.43	4.16	12.47	305	7.27	985
S	Sp-Sum	ONDJ	-1.33	2.81	3.50	3.42	339	3.74	825
	Sum-Fal	FMAM	-0.18	2.67	2.47	3.76	356	2.48	960
	Fal-Win	JJAS	-0.05	3.04	1.98	4.43	358	1.98	985

Figure 8 Net flow at all current observation stations occupied during the summer to fall season (February through May). Symbols as in Figure 6.

Figure 8

E/W Grid Loc. (J.S. Grid: ft)

Figure 9 Net flow at all current observation stations occupied during the fall to winter season (June through September). Symbols as in Figure 6.

Figure 9

E/W Grid Loc. (J.S. Grid: ft)

wastewater plume, with a high likelihood of plume transport toward the seawater intake area. Episodes of southward flow along McMurdo Station appear related to eddy decay during southward regional flow or to deflection of regional flow from the southwest by Hut Point. Currents at inshore stations (N, O, S) were less seasonally variable than outer stations (P, Q, R). Even though there were considerable seasonal shifts in current speed and direction, the major sources of variability for periodic (or cyclic) flow occurred on diurnal and, to a lesser degree, semidiurnal and shorter tidal periods (see below).

3.5 Principal Axes of Current Flow

Not surprisingly, analyses of the principal axes of motion for each current record indicated that major axes of flow were generally oriented on along-shore axes rather than cross-shore axes. The major axis of flow at nearly all stations was near 285 to 335 degrees (Table 4). Variation in the principal axes of flow among stations appears related to the changing coastline configuration and deflection of northward flow along McMurdo Station by Hut Point. Principal axes of flow were, however, not always coupled to the axis of net transport at each station (Table 4). Thus, even though currents generally flowed along the coast, currents sometimes switched direction over tidal cycles and seasons, resulting in residual motion along other axes.

Summaries of patterns of directional flow are presented in several figures. Polar projection graphs summarizing the frequency, speed, and total transport of currents in 15-degree interval compass headings are presented in Figures 10 through 16. Although these figures are somewhat difficult to understand, they provide a considerable amount of information concerning the frequency and speed that currents moved toward each compass heading. For example, Figure 10a, for Station N near the outfall pipe, indicates that currents flowed toward 330 degrees approximately 40% of the time. Moreover, the average speed of currents flowing toward 330 degrees was quite slow, near 3 cm/sec. Figure 10b indicates the total flow as a product of the percent of observations times the mean speed of currents in any direction. For Station N, it is clear that the vast majority of flow was toward about 330 degrees. Thus, most of the time, the wastewater plume is carried toward Hut Point, away from the station. Figure 10 also shows, however, that the plume flowed in a southeastern direction towards the intake area about 15% of the time, at a lower mean speed (~1.5 cm/sec). The distance the plume was transported in a southeast direction is a function of both the speed and the duration of currents. Figure 11 shows a similar pattern for currents at Station O. Flow was most frequently towards Hut Point, but currents did move toward the outfall area for a small but significant portion of the time, leading to significant transport in that direction. Station S (Figure 12) is apparently located on the inner arm of the McMurdo gyre, with current flowing nearly all of the time towards the north. This strong north to north-northwest flow is probably related to the turning of flow toward the north as it swings in with the southward area of the McMurdo gyre, which is likely located slightly to the southwest. Flow at Station S does reverse occasionally, with some transport to the south-southeast. Stations P, Q, and R (Figures 13 to 16) have very similar patterns of flow, owing to their close proximity to one another near Hut Point. All showed strong bi-directional flow, along north-northwest and south axes. Details of temporal variation in flow and the effects of current reversals on wastewater transport are discussed below.

Table 4 Summary of principal axes of flow at each station during 1992 to 1993

STATION	PRINCIPAL AXES				NET FLOW	
	Major Axis	Speed cm/s	Minor Axis	Speed cm/s	Heading	Speed cm/s
N	307	3.0	37	0.6	305	1.9
O	287	4.1	17	1.3	299	2.6
P	320	13.1	50	4.3	223	2.6
Q(top)	330	12.8	60	3.3	296	0.6
Q(bottom)	327	12.7	33	3.2	218	2.4
R	332	12.4	62	4.3	225	3.6
S	333	4.1	63	1.4	350	2.6

Polar Current Plot Station N

Percent Total Flow Station N

Figure 10 Polar flow diagram for Station N during December 1992 to November 1993. a. Frequency and speed of currents towards compass headings over all data. Dark line indicates the percentage frequency of all current vectors (3 h averages) for each 15 degree interval (e.g. 360 degrees = frequency from 331 to 360 degrees). Thin line is the mean speed for all observations within each 15 degree compass interval, in cm/s. b. Percentage of the total flow volume by compass heading. Dark line indicates the product of lines in a., standardized to 100%, such that the percentage of the total flow volume towards each compass interval is illustrated.

Polar Current Plot
Station O

Percent Total Flow
Station O

Figure 11 Polar flow diagram for Station O during December 1992 to November 1993. Symbols as in Figure 10.

Figure 12 Polar flow diagram for Station S during December 1992 to November 1993. Symbols as in Figure 10.

Figure 13 Polar flow diagram for Station P during December 1992 to November 1993. Symbols as in Figure 10.

Polar Current Plot
Station Q (top)

Percent Total Flow
Station Q (top)

Figure 14 Polar flow diagram for Station Q(top meter) during December 1992 to November 1993. Symbols as in Figure 10.

Polar Current Plot
Station Q (bottom)

Percent Total Flow
Station Q (bottom)

Figure 15 Polar flow diagram for Station Q(bottom meter) during December 1992 to November 1993. Symbols as in Figure 10.

Polar Current Plot
Station R

Percent Total Flow
Station R

Figure 16 Polar flow diagram for Station R during December 1992 to November 1993. Symbols as in Figure 10.

3.6 Temporal Variation in Regional Flow

3.6.1 Seasonal Variation

Currents at all stations varied considerably over daily, monthly, and seasonal periods. Some periods of motion were related clearly to known tidal motions controlled by planetary motions (see periodic flow below). Straw diagrams (Figures 17 to 21) present a year-long time series of individual current vectors for each station, averaged over 1, 3, 6, 12, and 24 hours. Figure 17 shows the 1-hour average for each current meter, including data for the entire year, and illustrates the great variation in both speed and direction from hourly to seasonal temporal scales. Long-term (e.g., monthly to seasonal) patterns of variation are more clearly evident from figures illustrating averages over longer periods (6, 12, and 24 hours). Strong southward flow in spring and summer, shifting to northward flow in winter and fall, is evident for Stations near Hut Point (P, Q, R) as well as those near the outfall (N, O, S). Current vectors averaged over longer time scales clarify the general pattern of flow at all stations. Comparison of Figures 19 through 21, showing 6, 12, and 24-hour mean current vectors from December 1992 to November 1993 for each station, provide a clear understanding of the general pattern of flow and the time scale of changes through the year. Figures 22 through 25 illustrate 6-hour vector averages for each 3-month period from December 1992 to November 1993 to provide greater clarity for current variation. These figures are useful when evaluating short-term shifts in current speed obscured by longer time series, but which are important events in transporting the wastewater plume southeast towards the seawater intake area. Stations near Hut Point (P, Q, R) all show much higher current speeds than those inside Hut Point. Because of the close proximity of Stations P, Q, and R, inspection of any one is sufficient to identify the current pattern near Hut Point.

Three distinct periods of flow are discernable from current records. These are spring-summer (October to January), summer-fall (February to May), and fall-winter (June to September). Currents were strong and nearly continuously southward near Hut Point during the spring-summer period, especially in December 1992 and January 1993. Flow at Stations N, O, and S was generally northward during this period, most evident from the 24-hour mean vectors (Figure 21). During the summer-fall period (February to May), currents were dramatically different from the spring period, perhaps due to the effects of sea ice degradation in McMurdo Sound and beyond, and the added influence of surface wind stress. During this period, currents oscillated in direction over periods of several days to a week or so near Hut Point. Interestingly, currents at the inshore stations (N, O, S) were less oscillatory and more persistently northward at this time. During the fall-winter period, currents near Hut Point shifted toward strong and persistent northward flow, with a few periods of reversal in direction toward the south, particularly in August and September. Onset of this pattern may be related to formation of extensive sea ice, removing the effects of wind stress seemingly evident in summer and fall. The recurrence of the summer-fall pattern in August may be related to sea ice removal by large winter storms. Inshore flow during the fall-winter period continued generally northwestward, with several reversals toward the southeast. This is particularly evident during June and July and is perhaps related to deflection of regional northeastward flow near Hut Point into Winter Quarters Bay and southeastward along the McMurdo Station shoreline.

Figure 17 Straw diagram illustrating a year-long time series of 1 hour average current vectors for current stations occupied in McMurdo Sound from December 1992 to November 1993. Individual 'sticks' represent single average vectors indicating the speed (length of stick) and direction of flow (direction of stick). Note the considerable variation over hours to seasons.

Current Vector Time Series

McMurdo Sound, 3h Means

Figure 18 Straw diagram illustrating a year-long time series of 3 hour average current vectors for current stations occupied in McMurdo Sound from December 1992 to November 1993

Current Vector Time Series

McMurdo Sound, 6h Means

Figure 19 Straw diagram illustrating a year-long time series of 6 hour average current vectors for current stations occupied in McMurdo Sound from December 1992 to November 1993

Current Vector Time Series McMurdo Sound, 12h Means

Figure 20 Straw diagram illustrating a year-long time series of 12 hour average current vectors for current stations occupied in McMurdo Sound from December 1992 to November 1993.

Figure 21 Straw diagram illustrating a year-long time series of 24 hour average current vectors for current stations occupied in McMurdo Sound from December 1992 to November 1993.

Current Vector Time Series

McMurdo Sound, Spring-Summer 6h Means

Figure 22 Straw diagram illustrating a time series of 6 h average current vectors at Stations in McMurdo Sound for the period December through February, 1993.

Current Vector Time Series

McMurdo Sound, Summer-Fall 6h Means

Figure 23 Straw diagram illustrating a time series of 6 h average current vectors at Stations in McMurdo Sound for the period March through May, 1993.

Current Vector Time Series McMurdo Sound, Fall-Winter 6h Means

Figure 24 Straw diagram illustrating a time series of 6 h average current vectors at Stations in McMurdo Sound for the period June through August, 1993

Current Vector Time Series

McMurdo Sound, Winter-Spring 6h Means

Figure 25 Straw diagram illustrating a time series of 6 h average current vectors at Stations in McMurdo Sound for the period September through November, 1993.

Patterns of flow for the year-long current meter observations during 1993 can be compared to all data available from 1991 and 1992 in Figures 26 and 27, showing straw diagrams of current vectors (averaged over 6 hours) for October through December 1991 and September through November 1992, respectively. Flow during 1991 and 1992 was quite similar to 1993. Flow at Hut Point, however, was more consistently southward than the same period in 1993, when there was greater northward flow during diurnal tidal shifts in flow.

3.6.2 Tidal Flow

Periodic flows are currents that are cyclic in nature, just as the tides rise and fall. The same gravitational effects of planetary motions that control the cyclic rise and fall of tides also produces cyclic currents over periods from hours to years. Currents associated with gravitational tides are known to be a dominant forces in McMurdo Sound (Barry and Dayton, 1988). Even though tidal motions are periodic, resulting in flow that oscillates in direction with little or no net transport of water, tidal currents can have important effects on transport of the McMurdo wastewater plume, even over scales of hours. Because periodic tidal motions over various temporal scales are superimposed upon each other, as well as other tidal motions (radiational tides) and aperiodic flow, actual transport of water by the sum of all driving forces may be relatively continuous in a particular direction (e.g., consistent southward regional flow during spring) or vary asymmetrically (greater flow in one direction of oscillation). Such variation in flow may have important effects on the induction or decay of the McMurdo gyre or other characteristics of inshore flow, thereby effecting transport of the wastewater plume.

Spectral analyses of current records for north-south and east-west components of flow at each station indicated strong tidal influences on current speed and direction. As expected from earlier studies (Barry and Dayton, 1988), the dominant frequencies for cyclic flow were near 24 hours (Figures 28 through 34), related to diurnal tidal constituents controlling astronomical, or gravitational, tidal currents. Diurnal tidal motions dominated east-west and north-south flow at all stations. Three frequencies near one cycle per day were discernable, corresponding to three or four diurnal tidal constituents (K_1 , O_1 , P_1 , Q_1 with periods of 23.93, 25.82, 24.07, and 26.87 hours, respectively). Higher frequency tidal motions were also evident at all stations. Secondary and smaller peaks in the power spectra were indicative of semidiurnal cyclic flow, associated with semidiurnal tidal constituents (M_2 , S_2 , and K_2 , with periods of 12.42, 12.00, and 11.97 hours, respectively). Oscillatory flow with frequencies near three cycles per day were less important overall, but still apparent, and are related to minor tidal constituents.

Dominance by diurnal and higher frequency tidal motions in the periodic current motions results in the greatest variation in flow (for cyclic flow) occurring on diurnal and shorter frequencies. Thus, planetary motions driving global-scale ocean tides are a principal feature regulating flow in and around McMurdo Sound, and these forces produce the diurnal and shorter period oscillations in flow evident in all current records.

Tidal variation in flow direction and speed are evident in several figures (e.g., Figures 17 through 19). For short-period observations or averages, short-period tidal oscillations are evident, but current observations that were averaged over long periods obscure shorter period motions. For example, 6- to 24-hour variation in flow (some associated with tidal effects) apparent in the 1-hour average straw diagram (Figure 17), are obscured in the 24-hour average data (Figure 21)

Current Vector Time Series 1991 McMurdo Sound, Spring-Summer, 6h Means

Figure 26 Straw diagram illustrating a time series of 6 h average current vectors at Stations in McMurdo Sound during October through December, 1991.

Current Vector Time Series 1992

McMurdo Sound, Spring-Summer, 6h Means

Figure 27 Straw diagram illustrating a time series of 6 h average current vectors at Stations in McMurdo Sound during September to November, 1992.

Station N

Figure 28 Power spectra for periodic flow at Station N. Power spectra are standardized to 1.0. Frequencies are in cycles per hour. See text for description of methods. a. Spectrum for north-south flow. b. Spectrum for east-west flow.

Station O

North-South o-93-1.01h, FFT length 2048, Hanning window, overlap 1024

East-West o-93-1.01h, FFT length 2048, Hanning window, overlap 1024

Figure 29 Power spectra for periodic flow at Station O. See Figure 28 for details. a. Spectrum for north-south flow. b. Spectrum for east-west flow.

Station P

Figure 30 Power spectra for periodic flow at Station P. See Figure 28 for details. a. Spectrum for north-south flow. b. Spectrum for east-west flow.

Station Q (top)

North-South q-93-1.01h, FFT length 2048, Hanning window, overlap 1024

East-West q-93-1.01h, FFT length 2048, Hanning window, overlap 1024

Figure 31 Power spectra for periodic flow at Station Q(top meter). See Figure 28 for details.
a. Spectrum for north-south flow. b. Spectrum for east-west flow.

Station Q (bottom)

Figure 32 Power spectra for periodic flow at Station Q(bottom meter). See Figure 28 for details. a. Spectrum for north-south flow. b. Spectrum for east-west flow.

Station R

North-South r-93-1.01h, FFT length 2048, Hanning window, overlap 1024

East-West r-93-1.01h, FFT length 2048, Hanning window, overlap 1024

Figure 33 Power spectra for periodic flow at Station R. See Figure 28 for details. a. Spectrum for north-south flow. b. Spectrum for east-west flow.

Station S

North-South s-93-1.01h, FFT length 2048, Hanning window, overlap 1024

East-West s-93-1.01h, FFT length 2048, Hanning window, overlap 1024

Figure 34 Power spectra for periodic flow at Station S. See Figure 28 for details. a. Spectrum for north-south flow. b. Spectrum for east-west flow.

because averaging all observations over 24 hours removes (filters) variation over periods less than 24 hours. Thus, tidal variation is expressed only in figures for data averaged over periods shorter than the tidal period in question. Although simple averaging of data points (e.g., averaging all 1-hour averages over 24 hours) effectively acts as a data filter, there are more effective data filters for removing tidal effects. Tidal periodicity over scales of about 30 hours and less was filtered using more sophisticated techniques from the data for Figures 42 to 48, which show both the raw data (1-hour averages) and filtered data.

Oscillatory flow on frequencies greater than 1 day were also evident, related to fortnightly and longer periods. Some small peaks in the power spectra from Stations N and O, and less so for other stations, indicate periodic flow on scales approaching biweekly or monthly cycles, corresponding to lunar fortnightly (M_f) and lunar monthly (M_m) tidal constituents. Unfortunately, even 1 year of data is insufficient to accurately discriminate cyclic patterns of flow occurring on seasonal periods. Even still, although seasonal shifts may occur consistently, there were clear changes in flow between seasons. Further study may reveal the nature of seasonal shifts in current flow. Another feature of the power spectra from all stations is the considerably noisier spectra for inshore stations (N, O, S), compared to stations offshore (P, Q, R). In particular, Stations N and O, nearest the outfall and Winter Quarters Bay, had much noisier spectra than other stations. This noise is related to the slightly lesser dominance of the diurnal, semidiurnal, and other strong peaks in the spectra for these stations. Topographic effects on local flow patterns, and the development and decay of the McMurdo gyre may have contributed to this aspect of these power spectra.

Factors in addition to gravitational effects of planetary motions also have strong influences on cyclic patterns of flow. So-called radiational tides are related to solar radiation, either directly (solar heating), or indirectly (via wind generation). Radiational tides can constitute up to 30% of gravitational tides (Pond and Pickard, 1983). In McMurdo Sound, the effects of radiational tides were not strongly evident in spectral analyses for relatively short periods (e.g., fortnightly or shorter), but may be great, particularly over seasonal periods during which the role of ice cover and wind stress on surface circulation may be evident. The observation period during this study, though extending nearly 1 year, is insufficient to identify the periodic characteristics of seasonal shifts in flow. Clearly, however, seasonal shifts were an important characteristic of the flow field near McMurdo Station.

3.7 Aperiodic Flow

Patterns of current flow unrelated to gravitational or radiational tides, or periodic flow undetectable from a 1-year current record, are an important component of flow near McMurdo Station. Overall, aperiodic flow can be estimated from the residual flow remaining after the effects of periodic motions have been removed. The easiest method of evaluating this is to average the horizontal (east-west) and vertical (north-south) components of currents over the entire data record. Table 2 lists a summary of current speeds for all stations from 1993 (Stations N-S), as well as all stations where current measurements were taken from 1991 to 1992 (Stations A-M). Current speeds are listed as the mean net speed (and standard deviation) and the mean absolute current speed for east-west and north-south axes. Net speed represents the mean speed overall, along the east-west or north-south axis, where east and north are positive. Absolute speed is the mean speed of currents along each axis, irrespective of direction. Note that

all stations sampled in 1993 (Stations N through S) had a net westward component of flow overall. The inshore stations (N, O, and S) had slow net northwestward flow and slow to moderate average absolute speeds on both east-west and north-south axes. Stations outside Hut Point were considerably more energetic, with absolute speeds over 10 cm/sec on the north-south axis, but relatively slow net drift, mostly to the southwest.

3.8 Progressive Vector Diagrams

Averages over the entire year do not adequately represent general conditions over time scales important to transport of the wastewater plume. Progressive vector diagrams for the year-long stations (N-S) illustrate much more clearly the pattern of flow between months. Progressive vector diagrams represent a time series of current vectors (e.g., straw diagram current vectors), attached head-to-tail. Thus, rather than a straw diagram with current vectors organized in series along a time axis, a progressive vector diagram represents the path of a water parcel during the measurement period, assuming that it flows in the direction and speed at which the current meter is positioned. In most cases, this is impossible, however, in that total transport approaches 1,000 km in many cases. Nevertheless, progressive vector diagrams illustrate quite clearly temporal changes in speed and direction of currents.

Progressive vector diagrams based on 3-hour vector averages for all year-long current observations (Figures 35 through 41) indicate that the pattern of flow for inshore stations (N, O, S) is considerably different than the offshore stations (P, Q, R). Offshore stations, representing the regional pattern of flow, are all quite similar. Flow at these stations was strong and consistent toward the southwest during December through mid-February, with some slight oscillations in speed and direction (Figures 35 through 38). About the time of sea ice breakout (February), the consistent southward flow ceased, and currents oscillated in direction from south-southwest to northwest until the beginning of June. These directional shifts occurred over periods of 2 to 3 weeks. Details of flow at Station Q (bottom) during this period are presented in Figure 36b, showing the daily oscillations (fine sawtooth pattern) superimposed on the biweekly-to-triweekly directional shifts. These daily excursions of the flow can transport water from 1 to perhaps 20 km. Commencing in early June, regional flow shifted to fairly strong and consistent flow to the northwest, with episodes of daily oscillation, particularly in early to mid-June and early July. During August, the strong northward flow ceased, with a more fall-like pattern of shifting southward to northwestward flow. Details of this flow pattern are illustrated for Station P in Figure 35b. During September, flow returned to the mid-winter pattern of northwest flow, and in spring (October to mid-November), flow once again shifted to a pattern of daily oscillating south to northwest flow.

Current meters deployed at different depths of Station Q (current meters at 22 and 42 m in 65-m water depth) had somewhat different patterns of net flow (Figures 36 and 37). The speed of flow was very similar, but the direction of flow differed somewhat. When flow was generally towards the south, each depth showed the same speed and direction. However, when flow shifted to generally north to northwestward, the deeper current meter had a slightly more westward direction of flow (about 35 degrees to west). This difference in flow is very likely due to frictional effects of the bottom. Meters at stations R and P, like the bottom meter at station Q, were about 10 to 20 m off the bottom, while the shallow meter at Station Q was 40 m above the bottom.

Progressive Vector Plot Station P : 3h means: Dec/92-Nov/93

Figure 35 Progressive vector plot for current vectors (3 h means) at Station P. a. December 1992 to November 1993. b. Details of late September through mid-November, 1993.

Progressive Vector Plot
Station P: (27m): Dec/92-Nov93

Progressive Vector Plot Station Q(bot): 42m: 3h means

Figure 36 Progressive vector plot for 3 h mean current vectors at Station Q (bottom meter).
a. December 1992 through November 1993. b. Details of flow during mid-February through mid-June.

Progressive Vector Plot
Station Q(bot): 42m: 3h means

Progressive Vector Plot Station Q(top): Dec/92-Nov93

Figure 37 Progressive vector plot for 3 h mean current vectors at Station Q (top meter), from December 1992 through November 1993.

Progressive Vector Plot
Station R: 3h means: Dec/92-Nov/93

Figure 38 Progressive vector plot for 3 h mean current vectors at Station R from December 1992 through November 1993.

Progressive Vector Plot
Site N: Dec/92-Nov/93

Figure 39 Progressive vector plot for 3 h mean current vectors at Station N. a. December 1992 through November 1993. b. Details of flow during mid-February through mid-January.

Progressive Vector Plot
Station N (15 m) : Dec/92-Nov/93

Progressive Vector Plot
Station O: 3h means : Dec/92-Nov/93

Figure 40 Progressive vector plot for 3 h mean current vectors at Station O. a. December 1992 through November 1993. b. Details of flow during mid-April through May.

Progressive Vector Plot
Station O : (27m): Dec/92-Nov93

Progressive Vector Plot
Station S: 3h means: Dec/92-Nov/93

Figure 41 Progressive vector plot for 3 h mean current vectors at Station S. a. December 1992 through November 1993. b. Details of flow during mid-May through June.

Progressive Vector Plot
Station S: 27m: Dec/92-Nov93

Progressive vector diagrams for inshore stations (N, O, S) showed a much different pattern of flow than offshore stations. Stations N and O had quite consistent flow towards the NW. In December and January, when regional flow was rapid and consistently southward, flow at Station N (Figure 39) was to the north-northwest (along-shore), and flow at Station O (Figure 40) was west to west-northwest. This was probably a period of McMurdo gyre formation and persistence. Although flow was generally northwest, the daily pattern of oscillatory flow is masked by the year-long time series. Details of the flow in late December and January at Station N are shown in Figure 39b. Even though flow was fairly consistent to the north (see Figure 39a), the northwest to southeast oscillations of daily tidal flow are evident. These daily excursions are on the order of about 0.5 to 1 km and may disperse the sewage plume toward the intake area to some degree. In general, however, flow is strongest to the northwest, away from the station. Similar oscillations are present during May and are shown in detail in Figure 40b for Station O. The jagged and elliptical cycles represent daily oscillations with the diurnal tides. Flow at Station S, a bit further offshore than the other inshore stations, was generally towards the north-northwest, roughly towards Winter Quarters Bay (Figure 41). This is the lower inshore sector of the McMurdo gyre, where flow has turned towards McMurdo and is heading up towards the McMurdo Station coast. Once again, the year-long time scale obscures shorter-term variations in flow. For example, flow during June is quite variable, even though regional flow (outer stations) was fairly strong to the north during this period. June flow at Station S had pronounced daily shifts from southeast to north-northwest (Figure 41b). The McMurdo gyre was probably not present during this period, and these oscillations were likely driven by tidally controlled changes in flow speed and general direction, coupled with the frictional effects of the shore.

3.10 Correlation in Flow Among Stations

Correlation analyses were used to compare relationships in flow speed and direction among stations. Overall, there was a highly significant positive correlation among stations P, Q, and R near Hut Point ($r > 0.85$; Table 5; for sample sizes greater than 1,000, r values > 0.081 are significant at the 1% level). Stations near Hut Point had slight negative correlations with inshore Station N, for both east-west and north-south flow. In contrast, Hut Point Stations were positively correlated, overall, with Station O, and showed a low positive correlation with Station S. These positive correlations are related mainly to the similar direction of flow through the McMurdo Station area during periods of regional northward flow. Tables 5b and 5c show a similar correlation coefficient matrix for periods of net southward and northward flow at station Q (top), respectively. When flow at Station Q (top) was northward, the correlation between Hut Point stations and Station O was much higher (0.41 to 0.55) than when flow is southward at Station Q (top) (0.09 to 0.16). Relationships among inshore stations varied. North-south flow at Station N was most highly correlated to Stations O and S when northward flow prevailed at Hut Point (when the McMurdo gyre was absent). During southward regional flow, east-west and north-south flow at Station N were positively correlated to east-west and north-south flow, respectively, at Station O, suggesting that northwestward flow along McMurdo Station turns westward with the McMurdo gyre during this period.

Table 5 Correlation coefficient (*r*) matrices for comparisons of flow among Stations. a. Coefficients calculated over all data. b. Coefficients derived from periods of southward NS flow at Station Q(top meter). c. Coefficients derived from periods of northward NS flow at Station Q(top meter). Values calculated from all data during 1992 and 1993. Values greater than 0.08 are significant at the 1% level of confidence.

A.

	Q(t):EW	Q(t):NS	N: EW	N: NS	Q(b): EW	Q(b): NS	S: EW	S: NS	R: EW	R: NS	P: EW	P: NS	O: EW	O: NS
Q(t):EW	1.00													
Q(t):NS	-0.82	1.00												
N: EW	-0.05	0.19	1.00											
N: NS	0.10	-0.22	-0.87	1.00										
Q(b): EW	0.92	-0.86	-0.07	0.11	1.00									
Q(b): NS	-0.86	0.95	0.15	-0.17	-0.89	1.00								
S: EW	0.15	-0.12	-0.21	0.13	0.15	-0.14	1.00							
S: NS	-0.12	0.16	0.22	-0.14	-0.16	0.18	-0.75	1.00						
R: EW	0.83	-0.83	-0.08	0.11	0.86	-0.86	0.13	-0.15	1.00					
R: NS	-0.77	0.94	0.22	-0.23	-0.77	0.92	-0.11	0.14	-0.81	1.00				
P: EW	0.88	-0.82	-0.18	0.20	0.90	-0.85	0.25	-0.25	0.86	-0.78	1.00			
P: NS	-0.79	0.91	0.23	-0.22	-0.80	0.90	-0.17	0.22	-0.79	0.92	-0.82	1.00		
O: EW	0.41	-0.26	-0.05	0.11	0.47	-0.33	0.22	-0.29	0.44	-0.20	0.55	-0.22	1.00	
O: NS	-0.47	0.49	0.25	-0.25	-0.54	0.50	-0.31	0.40	-0.56	0.46	-0.62	0.51	-0.54	1.00

B.

	Q(t):EW	Q(t):NS	N: EW	N: NS	Q(b): EW	Q(b): NS	S: EW	S: NS	R: EW	R: NS	P: EW	P: NS	O: EW	O: NS
Q(t):EW	1.00													
Q(t):NS	-0.81	1.00												
N: EW	-0.14	0.05	1.00											
N: NS	0.15	-0.07	-0.83	1.00										
Q(b): EW	0.87	-0.82	-0.12	0.12	1.00									
Q(b): NS	-0.82	0.93	0.08	-0.07	-0.82	1.00								
S: EW	0.15	-0.09	-0.17	0.05	0.11	-0.13	1.00							
S: NS	-0.09	0.05	0.13	0.01	-0.09	0.11	-0.74	1.00						
R: EW	0.82	-0.78	-0.16	0.14	0.79	-0.80	0.13	-0.10	1.00					
R: NS	-0.82	0.93	0.14	-0.11	-0.80	0.93	-0.15	0.11	-0.84	1.00				
P: EW	0.79	-0.74	-0.24	0.22	0.80	-0.74	0.20	-0.19	0.81	-0.79	1.00			
P: NS	-0.74	0.85	0.09	-0.03	-0.74	0.83	-0.15	0.17	-0.81	0.90	-0.77	1.00		
O: EW	0.08	0.11	-0.14	0.19	0.12	0.04	0.03	-0.12	0.02	0.07	0.16	0.19	1.00	
O: NS	-0.20	0.09	0.16	-0.15	-0.18	0.10	-0.25	0.34	-0.23	0.14	-0.29	0.13	-0.26	1.00

C.

	Q(t):EW	Q(t):NS	N: EW	N: NS	Q(b): EW	Q(b): NS	S: EW	S: NS	R: EW	R: NS	P: EW	P: NS	O: EW	O: NS
Q(t):EW	1.00													
Q(t):NS	-0.54	1.00												
N: EW	0.31	0.12	1.00											
N: NS	-0.22	-0.13	-0.90	1.00										
Q(b): EW	0.87	-0.71	0.20	-0.16	1.00									
Q(b): NS	-0.66	0.84	-0.07	0.04	-0.81	1.00								
S: EW	0.11	-0.08	-0.23	0.20	0.14	-0.10	1.00							
S: NS	-0.03	0.16	0.28	-0.24	-0.12	0.16	-0.77	1.00						
R: EW	0.69	-0.69	0.17	-0.12	0.75	-0.78	0.09	-0.09	1.00					
R: NS	-0.29	0.74	0.10	-0.12	-0.40	0.66	0.01	0.05	-0.62	1.00				
P: EW	0.80	-0.61	0.05	-0.01	0.84	-0.73	0.30	-0.26	0.77	-0.39	1.00			
P: NS	-0.49	0.78	0.24	-0.23	-0.66	0.78	-0.18	0.24	-0.65	0.66	-0.66	1.00		
O: EW	0.54	-0.35	0.09	-0.03	0.59	-0.49	0.33	-0.36	0.55	-0.17	0.79	-0.45	1.00	
O: NS	-0.40	0.55	0.23	-0.23	-0.51	0.55	-0.35	0.42	-0.51	0.45	-0.66	0.69	-0.62	1.00

3.11 Effects of Ice Cover and Wind Stress on McMurdo Sound Currents

Ice cover and wind are likely to have very strong influences on surface currents in McMurdo Sound, over local to large (e.g., 1,000 km) scales. The large seasonal shifts in current patterns are evidence of shifts in forces regulating flow in McMurdo Sound. While data are not readily available to accurately measure the timing and extend of sea ice cover, its removal near the beginning of February coincided with a marked shift in the prevailing pattern of flow near Hut Point, suggesting that the shift was a regional pattern. Week-long or longer episodes of prevailing south or northwest flow during fall and early winter may be associated with changes in wind stress regulated by the formation and removal of areas of sea ice near Ross Island and McMurdo Station. Similarly, the rapid northwest flow in June and July, followed abruptly by a return to oscillatory and generally southward flow in August, could easily be ice-related. Sea ice was developing through fall and may have reached near maximum development around Ross Island by the beginning of June, only to be removed by a harsh winter storm of early August. Thus, it appears that reduction of ice cover results in generally southward surface currents near McMurdo Station, in response to wind stress.

4. DISCUSSION

4.1 Relationship of Current Patterns to Wastewater Plume Dispersal

Year-long observations of currents in the vicinity of McMurdo Station revealed large variation in ocean currents that had not been identified from data collected solely during spring and early summer. Spring and early summer studies during 1991 and 1992 showed that the regional pattern of flow was generally southward along the Hut Point Peninsula, and generated a counter-clockwise eddy adjacent to McMurdo Station (McFeters et al., 1993). Flow in this eddy transports the wastewater plume from the present outfall towards Hut Point, where it presumably is entrained in southward flow passing Hut Point and is dispersed away from McMurdo Station. The transport mechanism does not transport solids that settle to the bottom in the outfall area, where low current speeds dominate (Table 2). Importantly, episodes of current reversal along McMurdo Station, which persisted for 12 to 24 hours, were evident in current records approximately monthly during spring, resulting in plume transport to the southwest towards the seawater intake. This mechanism is probably responsible for the high coliform bacterial densities near the seawater intake area (Howington et al., 1992; McFeters et al., 1993).

Year-long observations during 1992 to 1993 indicated a similar flow pattern with general consistent net directional flow (seasonally variable in direction), coupled with significant daily to fortnightly oscillations in current speed and direction. Variation in the flow field over even semidiurnal to diurnal time scales may have important consequences in transport and dispersal of the wastewater plume, considering the short distances required for overlap of the plume with the seawater intake area. It is roughly 500 m from the present outfall pipe to the seawater intake pipe. Transport of this distance will require only 6 hours for a current running southwest at 2.5 cm/sec (the average current speed near the outfall).

Another consideration apparent after a third year of observations and inclusion of observations from all seasons is the importance of the coupling of diurnal motions with longer period changes in regional flow. For example, if diurnal tidal oscillations in current speed and direction are superimposed on a fairly rapid southward large-scale flow along the Hut Point Peninsula, the combined current will be a pulsed southward flow, oscillating from sluggishly (e.g., near 3 cm/sec) southward (when the tidal flow opposed the larger scale flow) to rapidly southward when tidal flow reverses (e.g., 20 cm/sec; Figure 26, Station A). During these periods, the McMurdo gyre should be relatively persistent, and transport near the present outfall will be towards Hut Point. However, if the larger scale flow is weakly southward, northward periods of tidal oscillation can result in net northward flow near Hut Point, perhaps disrupting the McMurdo gyre and transporting the wastewater plume to the southeast. Likewise, tidal oscillations superimposed on net northward regional flow may also have important consequences near McMurdo Station.

Coupling of several scales of variation can result in episodes of current reversal along the McMurdo Station shoreline, with sufficient magnitude to disperse the wastewater plume near McMurdo Station, rather than transport much of it offshore. Figures 42 through 48 illustrate coupling of tidal and aperiodic flow. For each station, hourly current speeds are shown in gray for north-south and east-west directions of flow. Net current speeds for hourly data with tidal

Current Speed (Absolute, Low-Pass Filt.)

Figure 42 Time series of 1 h average current speeds at Station P, including unfiltered data (gray) and low-pass filtered data (black). See text for explanation of filtering. a. North-South flow. b. East-West flow.

Figure 43 Time series of 1 h average current speeds at Station N, including unfiltered data (gray) and low-pass filtered data (black). See text for explanation of filtering. a. North-South flow. b. East-West flow.

Current Speed (Absolute, Low-Pass Filt.)

Figure 44 Time series of 1 h average current speeds at Station O, including unfiltered data (gray) and low-pass filtered data (black). See text for explanation of filtering. a. North-South flow. b. East-West flow.

Current Speed (Absolute, Low-Pass Filt.)

Figure 45 Time series of 1 h average current speeds at Station S, including unfiltered data (gray) and low-pass filtered data (black). See text for explanation of filtering. a. North-South flow. b. East-West flow.

Current Speed (Absolute, Low-Pass Filt.)

Figure 46 Time series of 1 h average current speeds at Station R, including unfiltered data (gray) and low-pass filtered data (black). See text for explanation of filtering. a. North-South flow. b. East-West flow.

Current Speed (Absolute, Low-Pass Filt.)

Figure 47 Time series of 1 h average current speeds at Station Q(top meter), including unfiltered data (gray) and low-pass filtered data (black). See text for explanation of filtering. a. North-South flow. b. East-West flow.

Current Speed (Absolute, Low-Pass Filt.)

Figure 48 Time series of 1 h average current speeds at Station Q(bottom meter), including unfiltered data (gray) and low-pass filtered data (black). See text for explanation of filtering. a. North-South flow. b. East-West flow.

motions of 30 hours and less filtered out are shown in black. Thus, the black lines indicate the pattern of transport over short periods, after tidal oscillations are removed. Figure 43, for Station P (Stations P, Q, and R are very similar) represents flow near Hut Point, and shows the highly variable tidal fluctuations present in hourly averages (gray) for December and January, and less variable and consistent net southwestward flow of tidally filtered averages (black). At the same time, filtered net flow at Station N (Figure 44) was usually to the northwest, but there were occasional shifts to the southeast. The period January 31 to February 1 was a one such period of reversal evident both at Hut Point (Figure 43) and at Station N (Figure 44), with sufficient speed and duration to transport the plume toward the intake area. This event was not clearly evident at Stations O or S (Figures 45 and 46), suggesting that flow may be more complex than a 2-phase system either with or without a counter-clockwise gyre. The gyre may degrade, change size, or spin off, producing complex patterns of flow, at least over short time scales. A similar event in mid-February is evident at nearly all stations. Flow reversed near Hut Point to northeastward transport, and southeastward at Station N. Flow at Station S shifted from north-northwest to southeast, and at Station O, flow shifted from northwest to northeast. This indicates that the McMurdo eddy dissipated or released from the coast, and flow turned into Winter Quarters Bay near Hut Point, then travelled along the coast towards the intake area.

The frequency of reversal events, or any event [defined as a current observation at Station N with sufficient speed to transport the plume 500 m to the southeast (120–165 degrees)] sufficient to impact the intake area ranged from 1.2 to 6.7%. For 3-hour mean data at Station N, 2.3% of 2,770 total observations were both toward the southeast and 4.6 cm/sec or greater. For 6-hour data averages, flow was to the southeast 18.3% of the time, and 5.3% of 1,367 observations had sufficient speed to carry the plume 500 m during the 6-hour period. For 12-hour averages, the plume could move to the southeast at least 500 m 6.7% of the time. Thus, although southeast flow near the outfall comprises a minority of the flow patterns in that areas, these events are clearly an important component of the flow field capable of relatively frequent impacts to the intake area.

During other seasons, the regional pattern of flow was considerably different than December through January, leading to variation in flow along McMurdo Station. In general, flow was northward at Station N near the outfall (Figure 44), but episodes of reversals to southeast flow were apparent throughout the year. Although these are minor variations compared to the major seasonal changes, they are sufficient to modify the local dispersal of the wastewater plume and disperse coliform bacteria throughout the McMurdo shoreline.

4.2 Recommendations for Wastewater Outfall Relocation

In view of several problems with wastewater release into waters very near McMurdo Station (i.e., the present outfall pipe site or inshore of this site), the outfall pipe should be relocated further offshore, in a location penetrating the mainstream or regional flow near McMurdo Station. Problems with wastewater release at the present site include (a) episodic southeast transport towards the seawater intake, related to the outfall position within the McMurdo gyre, (b) dispersal of wastewater towards the tidal crack or other areas close to shore, and (c) chronic degradation of relatively rare soft-sediment habitats in and around Winter Quarters Bay (Lenihan et al., 1990). The problem of episodic reversals in flow was discussed thoroughly above. Another consequence of such reversals, and perhaps related to nearshore release of McMurdo wastewater

during all periods, is entrainment of wastewater very near shore where frictional effects trap the plume near the shore, where it very likely disperses along-shore via tidal motion. Few data are available to evaluate the mechanisms controlling this process. Moreover, currents may, at times, be considerably more complex than a simple gyre with northwest along-shore flow near Station N. Instead, small eddies or other current features may disperse the plume within the McMurdo Station area regardless of current reversals. Because these habitats are somewhat rare (few habitats dominated by fine sediments are present along Ross Island), it is desirable to minimize inputs of dissolved or particulate contaminants (i.e. wastewater) to this area.

The ideal location for a wastewater release site is one providing the maximum likelihood of entrainment of the wastewater plume in currents that disperse the plume downstream and offshore from McMurdo Station. In addition, a site of high-current speeds is preferable to one of low speeds, owing to the greater potential for resuspension and removal of sinking particulate material. Near McMurdo Station, this requires the site to be outside the McMurdo gyre so that the plume is not entrained in the gyre and transported inshore. Figure 49 shows an area potentially appropriate for the outfall site. The boxes indicate regions thought to be minimally away from the McMurdo gyre to prevent entrainment of the plume. The proposed locations should be compared to maps indicating the seasonal pattern of flow near the station. In particular, inspection of the spring-summer map (Figure 7) shows the transition zone between the inner and outer portions of the McMurdo gyre (Stations J, K, and L) during a 1-month-long current record from 1992. Station J is clearly in the inner side of the gyre, and station L is in the outer portion of the gyre. Station K is located in the central transition zone of the gyre. The gyre very likely varies considerably in its size and position. To maximize dispersal away from McMurdo Station, the outfall should be positioned at least as far offshore as Station L, and preferably much farther, since flow from Station L probably turns towards the coast as part of the McMurdo gyre. The advantage of positioning the outfall directly offshore from Hut Point, in addition to distance from the McMurdo gyre, is the higher current speeds in this area, and potential for dispersal of solids. A negative aspect of this site is the potential for entrainment of wastewater into the plume; because Hut Point is the point of generation for the gyre, the nearer to Hut Point the outfall is placed, the greater the likelihood for entrainment in the gyre. Nevertheless, any site outside the gyre is preferable to the present location. Again, the maximum distance offshore is the preferred location. Variation in flow may result in plume transport inshore, even from offshore of this location. During winter of 1993, there were periods when the regional flow appeared to be directed nearly from the southwest, which will transport offshore waters directly towards McMurdo Station. Under such conditions, it would be difficult to position the outfall pipe anywhere within several kilometers of McMurdo Station and prevent some plume transport to the McMurdo vicinity. However, during periods of regional flow in directions from about 160 to 360 degrees true, the plume should be dispersed away from McMurdo Station from this location.

An additional consideration for outfall positioning is the pipeline track, which should optimally continue downslope with no upsloping sections. Although the bathymetric map (Figure 5) is quite coarse in scale, it was used to identify the generally preferred pipeline track. This track may be modified according to results of a more detailed bathymetric survey.

Figure 49 Map of McMurdo Sound near McMurdo Station indicating proposed wastewater pipeline and outfall sites. Black line indicates the proposed pipeline path. Light brown area indicates the region with optimal current flow patterns for waste dispersal away from McMurdo Station.

Figure 49

E/W Grid Loc. (J.S. Grid: ft)

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Appendix A

Computer-Based Time Series of McMurdo Sound Current Vectors

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Computer-Based Time Series of McMurdo Sound Current Vectors

A-1. Description of Vector Display Program

With considerable support from Sean Callahan of the Crary Science Facility at McMurdo Station, we developed a computer program to display time series observations of current vectors for all current meter records from 1991 to 1993. This program (VECTOR) reads data files for 1, 3, 6, 12, or 24-hour mean current vectors for all stations and provides a graphic display on a DOS-based computer terminal. VECTOR is useful in inspecting patterns of flow, and particularly, variation in flow over time. Individual vectors corresponding to observations from each station at each time period are displayed simultaneously to provide an instantaneous synoptic view of currents near McMurdo Station. The time series can be paused, accelerated, or slowed, depending on the desired rate of inspection. As time series of data for each station are completed, a mean overall vector average is displayed in a different color to allow discrimination between these and instantaneous vectors. VECTOR is provided on a 3.5-in. floppy disk and is accompanied by data files comprising 6, 12, and 24-hour averages.

VECTOR is initiated by copying all files on the diskette to a hard disk (though it will run from the floppy), and typing the command `vector`. The program will begin and list all available data files. Choose the file type (6, 12, or 24-hour averaged data) by typing the appropriate code (e.g., `*.12h` for 12-hour averages). You may also select individual files by their specific names. Press the return key when you are finished with data selection (select only one type of data: 6, 12, or 24-hour averages), and VECTOR will read all appropriate data files and begin displaying data. Current vectors will be displayed as they are available for each station, according to the time clock, which begins at the beginning of the available data, and increments in time according to the data type (i.e., 6, 12, or 24 hours).

A-2. Description of Vector Keyboard Controls

Keyboard controls can be used to modify the display rate and other characteristics of the VECTOR program. These keyboard controls can be used in upper or lower case and have immediate effects on program display features. When the program is complete, it will flicker, with blue current averages displayed for each station or data file. Data averages displayed at the end of each data series are not affected by advancing the time clock (e.g., M).

The following are the keyboard controls:

VECTOR	Start program
Space bar	Pause or resume operation
+	Speed clock by factor of 2
-	Slow clock by factor of 2
>	Increase current vector scale
<	Decrease current vector scale
D	Advance clock by 1 day
M	Advance clock by 1 month
Y	Advance clock by 1 year
R	Redraw coastline