THE EXCHANGE OF WATER BETWEEN

PRINCE WILLIAM SOUND AND THE GULF OF ALASKA

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A

THESIS

Presented to the Faculty of the

University of Alaska in partial fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

by

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Fairbanks, Alaska

May 1977

ABSTRACT

Prince William Sound is a complex fjord-type estuarine system bordering the northern Gulf of Alaska. This study is an analysis of exchange between Prince William Sound and the Gulf of Alaska. Warm, high salinity deep water appears outside the Sound during summer and early autumn. Exchange between this ocean water and fjord water is a combination of deep and intermediate advective intrusions plus deep diffusive mixing. Intermediate exchange appears to be an annual phenomenon occurring throughout the summer. During this season, medium scale parcels of ocean water centered on temperature and NO maxima appear in the intermediate depth fjord water. Deep advective exchange also occurs as a regular annual event through the late summer and early autumn. Deep diffusive exchange probably occurs throughout the year, being more evident during the winter in the absence of advective intrusions.

ACKNOWLEDGMENTS

Appreciation is extended to Dr. T. C. Royer, Dr. J. M. Colonell, Dr. R. T. Cooney, Dr. R. D. Muench and D. T. Heggie for their advice and encouragement. The data were obtained from the archives of the Institute of Marine Science, University of Alaska. This work was supported through the Office of Sea Grant, Department of Commerce under Grant No. 04-3158-41 and the Alyeska Pipeline Service Company, TAPS/41 to 12 Ammendment #12.

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1. INTRODUCTION

In the fjord-type estuaries along the coasts of Alaska, Canada and Norway, exchange between the fjord water and coastal ocean water is an important part of the circulation regime. This study is an analysis of exchange between Prince William Sound and the Gulf of Alaska.

1.1. Prince William Sound

Prince William Sound is a complex fjord-type estuarine system bordering the northern Gulf of Alaska (Fig. 1). Lying under the arc of the Chugach and Kenai Mountains, the Sound is bounded on the east by the Copper River and on the west by the Kenai Peninsula (145°37' to 148°43'W, 59°46' to 61°16'N). Surrounded by several outward-radiating fjords, the Sound connects with the Gulf via Hinchinbrook Entrance and Montague Strait with limited access through the archipelagic islands at the east and west (Fig. 2). Prince William Sound is 92 km in lateral and 56 km in longitudinal dimension, covers 8,835 km^2 and has a total coastline in excess of 3,200 km (Grant and Higgins, 1910). Most of the shore line is mountainous, resulting in a restricted drainage basin. The climate is maritime, with moderate temperatures and heavy precipitation.

The Prince William Sound basin was formed by a combination of preglacial erosion, glacial excavation and tectonism. Prior to the first glaciation, the coastal mountain chains were formed. Over one million years ago during the Pleistocene, Prince William Sound was covered by an ice sheet over 1,000 m thick which extended into the Gulf of Alaska

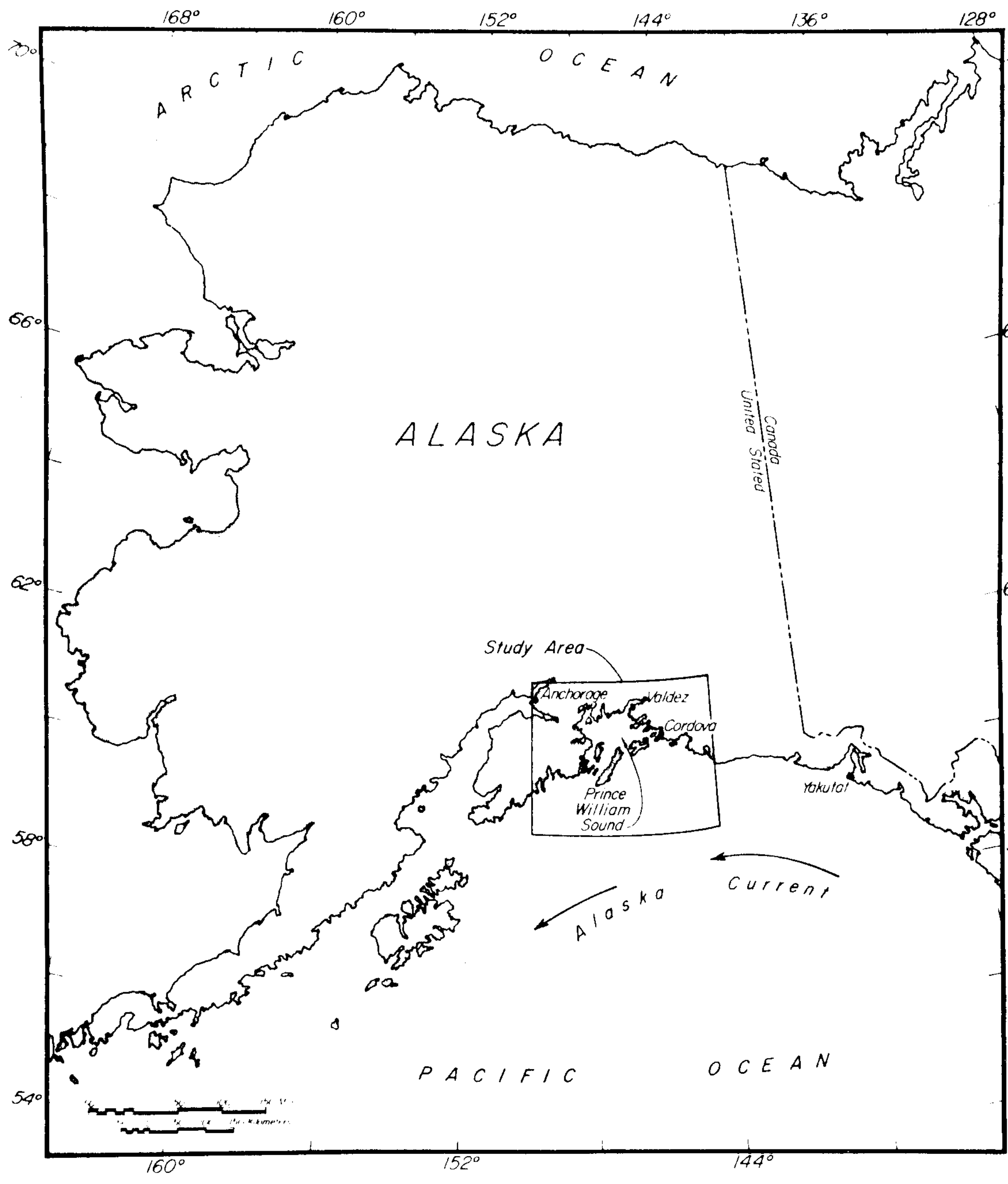

Figure 1. Geographic location of Prince William Sound.

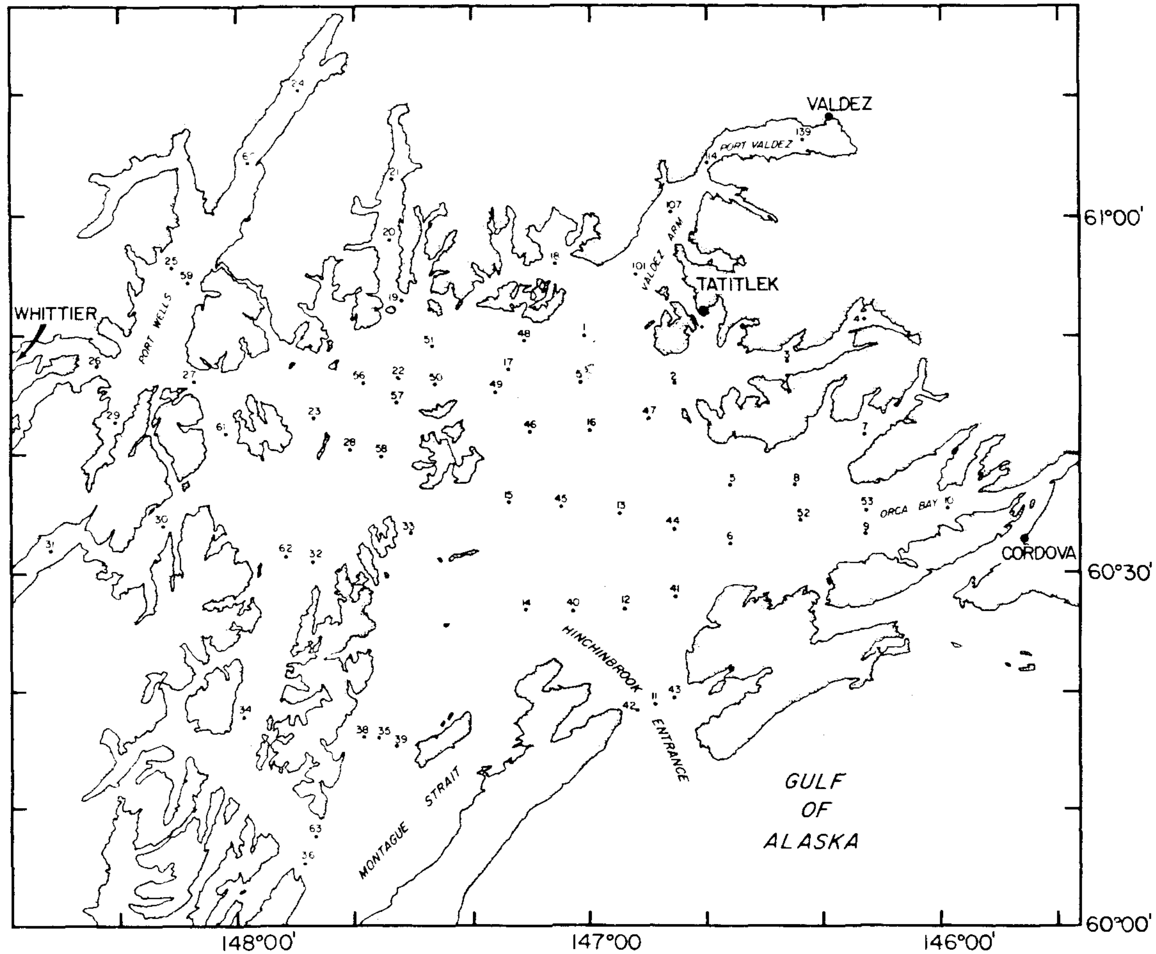

Figure 2. Location of Prince William Sound stations.

through Hinchinbrook Entrance as far as Middleton Island (Grant and Higgins, 1910). This ice sheet dug deep basins in the preglacial lowlands (Tarr and Martin, 1914). Around 10,000 years ago, glacial retreat started and deposited unconsolidated glacial drift over the basement rock in irregular strata (Walters, 1963). At this time, sea-water probably filled the Sound. Over these strata, more recent Holocene sediments were deposited from streams, glaciers, mass wasting and sediment transport from the Copper River (von Huene, 1967). Recent sediments have become slightly faulted and folded. However, seismic profiling work of von Huene (1967) has indicated that the basin reacts to recent tectonism without severe faulting.

The Sound was originally inhabited by eight tribes of the Chugach Eskimo or cuatit as they called themselves, who lived by subsistence hunting and fishing (de Laguna, 1956). As early as 1740, Bering sailed along the Alaska coast making contact with the Chugach on Kayak Island (Golder, 1968). In the summer of 1778, Captain James Cook sailed into the Sound and named it after the son of Britain's King George the Third (Beaglehole, 1967). Further exploration by the Spanish, particularly Salvador Fidalgo, took place during the late 1700's (Grant and Higgins, 1910). Vancouver prepared charts of the region during this time (Hulley, 1953).

Aside from several short lived economic booms, Prince William Sound has seen little change during the past 200 years. Russian "promyshleniki" or professional hunters and fur traders (McCracken, 1957) harvested sea otters to near extinction during the late 1700's and 1800's. Copper mining thrived during the early 1900's until the rich veins were depleted.

Prior to World War II, large scale fox breeding for the fashion industries was practiced on islands throughout the Sound (Hulley, 1953). Some reconstruction and research followed the devastation of the 1964 earthquake. Commercial fishing has been the only enterprise to flourish continuously during this time. The original native population of about 1,500 was reduced to less than 500 by smallpox during the late 1830's (Hulley, 1953) and the present population numbers less than 5,000, most of whom reside in Valdez, Cordova, Whittier and Tatitlek. Prince William Sound now faces major development as the receiving-loading area for the trans-Alaskan oil pipeline. It is also experiencing recreational and urban stresses from Anchorage and increasing pressure from commercial fishing.

1.2. Background Fjord Literature

Prince William Sound may be classified as an estuarine system on the basis of Pritchard's (1967) definition. The determining factor here is that salinity differences between the Sound and the Gulf do exist throughout the year (Muench and Schmidt, 1975; Royer, 1975). However, due to the limited freshwater input, the Sound may become more like a simple bay than an estuarine system during the winter months. The work of Carlson *et al.* (1969) allowed Muench and Nebert (1973) to classify Port Valdez as a low freshwater input estuary. Similar classification of the Sound is reasonable. The relationship between basin formation and glaciation is discussed above and allows classification as a fjord-type estuary even though faulting and local subsidence are factors. However, the Sound may not be an "ideal" fjord in Rattray's (1967) terms, as tidal mixing may be as important as the limited freshwater input.

The past work in the fluid mechanics and estuarine hydrodynamics has laid a sophisticated foundation for contempory research. Estuaries, particularly the coastal plain type, have been defined, classified and analyzed (Pritchard, 1954; 1956; 1958; 1967). Qualitative analyses of the fjord-type inlets of British Columbia and Southeast Alaska have been done (Pickard, 1956; 1961; 1967). The circulation and deep water exchange in Norwegian fjords has been studied (Saelen, 1967; Gade, 1970). Finally, theoretical investigations of fjord dynamics have been carried out (Rattray and Hansen, 1962; Rattray, 1967).

In spite of the depth and extent of estuarine research, little work has been directed to subarctic Alaskan fjord systems which are exposed to harsh and widely varying climatic conditions throughout the year. The physical oceanography of several Alaskan fjords including Endicott Arm (Nebert and Matthews, 1972), Resurrection Bay (Heggie and Burrell, 1973), and Russel Fjord (Reeburgh *et al.*, 1976) has been studied. An intensive hydrographic survey has been carried out in Port Valdez (Muench and Nebert, 1973) and work will continue there. Annual cycling of water mass characteristics on the northern shelf of the Gulf of Alaska has been described (Royer, 1975). Seasonal changes in the hydrographic structure, circulation and mixing in Prince William Sound have been qualitatively discussed (Muench and Schmidt, 1975).

1.3. Deep Water Exchange

Deep water exchange is defined as the replacement of fjord water below sill depth. The exchange is with either intermediate fjord water or nearby coastal ocean water. This exchange mechanism occurs primarily through advective inflows, supplemented by turbulent diffusion and thermohaline convection. When the density of the marine source water at sill depth and above becomes greater than that of the fjord water, inflow can occur (Gade, 1973). Flowing along its own density surface, the source water can interleaf with the intermediate or deep fjord water or flow along the fjord bottom uplifting the deep water. In addition to these density-driven advective flows, wind-induced surface outflow and subsequent inflow at deeper layers can occur. To a large degree, vertical eddy diffusion between deep and intermediate water is generated by tidal currents with possible superimposed systems of standing and progressive internal waves (Gade, 1970; Stigebrandt, 1976). To a lesser extent, wind stress (Muench and Nebert, 1973) and sea ice formation in certain regions (Nutt and Coachman, 1956) can contribute to vertical exchange through convective mixing to the deep or bottom water.

This inflow of marine source water over a sill and through a narrow strait or entrance is a complicated hydrodynamic problem which has been modeled by Whitehead (1974, 1975). A uniform vertical current profile during subsequent inflow and outflow is not always the case in a narrow channel. An extreme example of this complicated inflow exists in Rupert and Holberg Inlets on Vancouver Islands (Farmer, 1975) where the flood tide produces a jet of water near the surface which sinks to the bottom after intense tidal mixing. "Bolus-type" influxes of source water have also been observed (Anderson and Devol, 1973; Ebbesmeyer, 1973; Reeburgh *et al.*, 1976). The generation and dissipation of internal waves at the sill due to inflow of a stratified fluid as modeled by Stigebrandt (1976) can be an important mixing process. This tidal mixing can be very important to variations in primary production and the distribution of suspended sediments (Ingram *et al.*, 1975). The importance of wind stress to deep inflows has been suspected for some time and the correlation of deep current measurements with surface wind measurements in Resurrection Bay support this (Heggie and Burrell, 1974). With the influx and mixing, bouyant forces cause the water to settle to its own density level and to displace resident water which can then be advected out of the fjord on subsequent tides.

Considerable differences exist in the characteristics of deep water exchange in various fjords. The depth and location of the sill, size and shape of the deep basin, seasonal variations in the source water and fluctuations in meteorological conditions all contribute to these differences. In order to describe deep water exchange in Prince William Sound and relate it to other fjords, it is helpful to use some standard terms.

The exchange of deep fjord water can be described by its extent, duration, frequency and regularity. Deep fjord water lies below sill depth, while intermediate water occurs between the surface estuarine or mixed layer and the sill depth. The deep water can be exchanged to the extent that it is completely replaced, i.e., renewed or only partially replaced. This fractional replacement seems to be more common in fjords with large deep basins. The duration of the exchange can range from a rapid spontaneous event lasting a tidal cycle (Gade, 1973) to a continuous and ongoing process occuring over long time intervals (Nebert and Matthews, 1972). Various degrees of intermittent exchange exist between these extremes. Sudden large density increases in the source water can generate rapid exchanges, especially when the deep water is isolated behind a shallow sill. The frequency and regularity of deep water exchange is described and defined by Gade (1973). "The replacement of resident fjord water is characterized by some sort of regularity, i.e., the influxes tend to take place at the same time each year." Seasonal variations in source water and meteorological conditions are determining factors here. The frequency or time interval between non-continuous exchanges can be periodic, sometimes occuring at intervals of once a year. The combination of a shallow silled fjord and unusual density fluctuations in near surface source water can result in several years elapsing between exchanges.

1.4. The Thesis Hypothesis

Fractional exchange of deep water in Prince William Sound is predicted annually through advective inflows in the late summer or autumn and continuously through vertical diffusion during most of the year. This hypothesis is derived from information on the annual cycling of water mass characteristics in the Gulf of Alaska (Royer, 1975) and deep water exchange in Resurrection Bay (Heggie and Burrell, 1973).

Annual cycling of water mass characteristics in the Gulf of Alaska (Royer, 1975) results in a regular density maximum during early autumn (Fig. 3). If it is assumed that the fjord water is less dense than the summer source water, then advective inflows can occur, being most likely

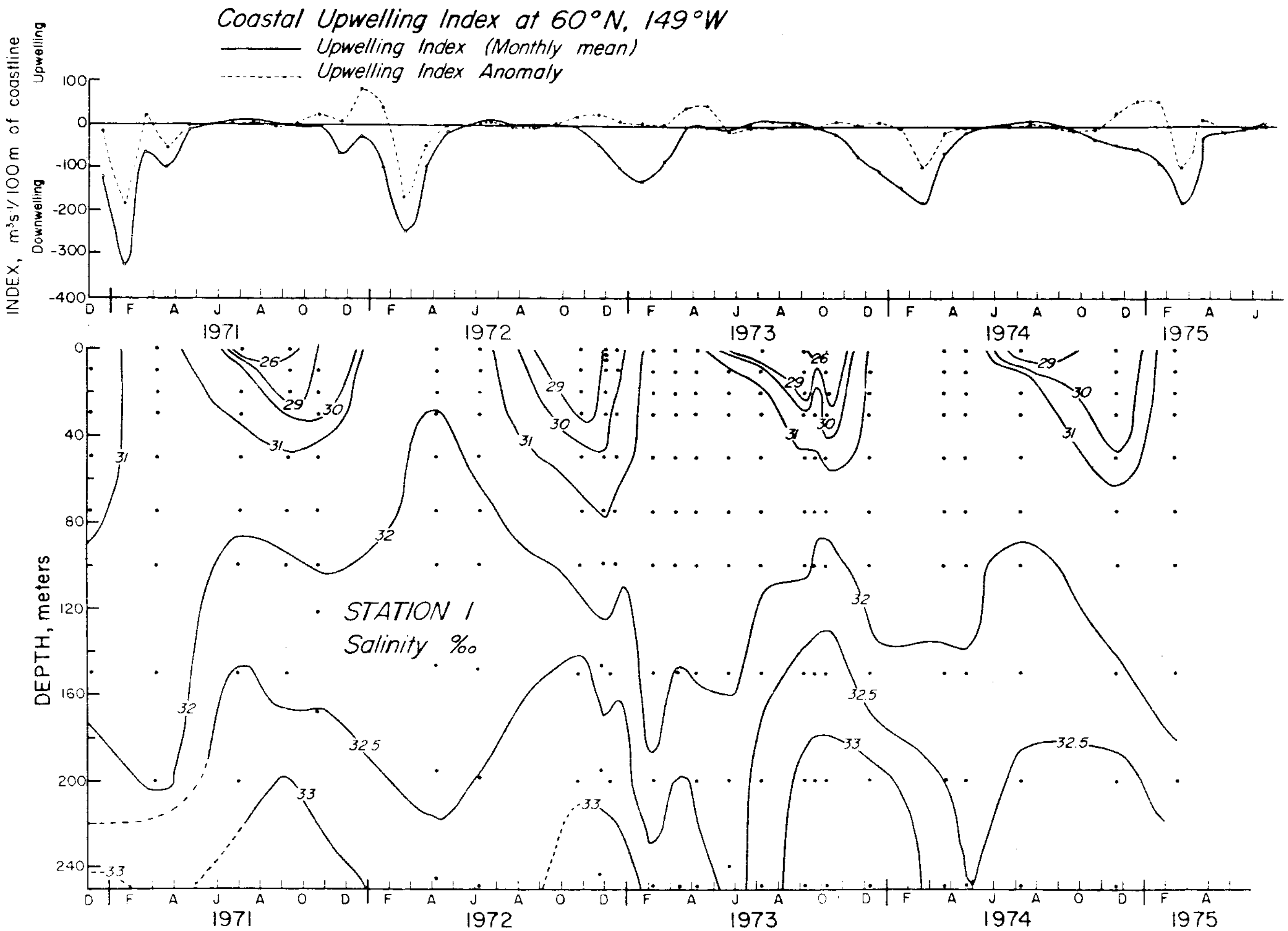

Figure 3. Time series of salinity for GAK 1 in the Gulf of Alaska with monthly mean upwelling index and its anomaly (Royer).

in late summer or early autumn. The observed autumn density maximum is probably an annual phenomenon varying in degree from year to year. The extent of exchange would increase with the magnitude and duration of the density difference. Heggie and Burrell (1974) have shown correlation between winds blowing out of Resurrection Bay and deep advective inflows. These winds may serve to trigger inflow once dense source water appears outside the sill. Applying this mechanism to Prince William Sound is uncertain since the bathymetry and surrounding topography are quite different from those of Resurrection Bay.

Significant turbulent mixing is expected as a result of the large tidal ranges and currents (U.S. Dept. of Commerce, 1971-1975) moving in the narrow straits and irregular bathymetry of the Sound. Exchange through vertical mixing could result continuously through the year, being more evident during the winter when advective inflow is least likely.

2. DATA

2.1. Cruise Summary

Scattered oceanographic stations involving measurements of temperature, salinity, dissolved oxygen and nutrients were occupied during the summers of 1955, 1959, 1966 and 1969 by various institutions. As part of an oceanographic survey of Port Valdez, six stations were occupied in eastern Prince William Sound at approximately bi-monthly intervals from May 1971 through April 1972 (Muench and Nebert, 1973). An expanded sampling program in Prince William Sound was started in March 1972 and continued through May 1973. Some data were obtained on cruises of opportunity in the Sound during 1974 and 1975. In March 1976, hydrographic sampling in Port Valdez and Prince William Sound was resumed.

The physical oceanography of the northern continental shelf of the Gulf of Alaska has been studied since December 1970 (Royer, 1975). Beginning in December 1970 to October 1972, a line of eleven stations running southeast out of Seward (Fig. 4) was occupied. From November 1972 until the present, station GAK 1 on this line was occupied. Starting in July 1974 and continuing through the present, work in the eastern Gulf has been expanded to cover over sixty stations from Seward in the west to Cape Yakutat in the east. The Hinchinbrook station line was extended into Prince William Sound (PWS 12, 13, 55 and 101). These data are providing valuable information on the nature of source water available to the Sound at Hinchinbrook Entrance.

Table 1 summarizes the cruises to Prince William Sound and Tables 2 and 3 those to the Gulf of Alaska. Figure 2 and 4 and Appendix A give

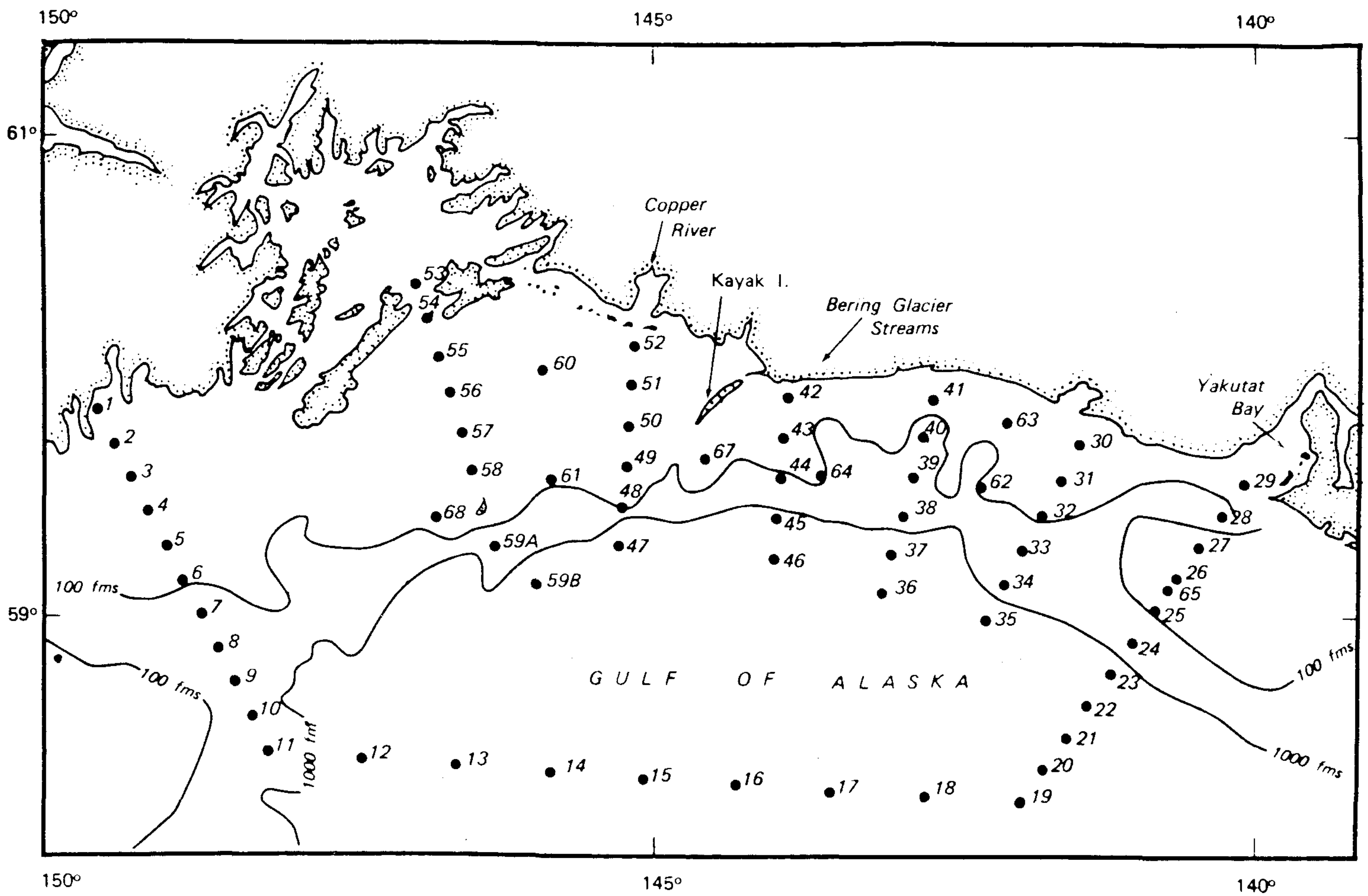

Figure 4. Location of Gulf of Alaska stations (Royer).

TABLE 1

SUMMARY OF DATA COLLECTED FROM PRINCE WILLIAM SOUND

Year	Month	Number of Stations	Measurements	Ship	Cruise Number
1955	August	3	T, S, O_2, N	*Brown Bear*	310748
1959	May	13	T, S, O_2	*Bowie*	310520
1966	July	94	T, S, O_2	*Acona*	26
1969	August	35	T, S, O_2	*Ursa Minor*	503
1971	May	6	T, S, O_2, N	*Acona*	113
1971	July	6	T, S, O_2, N	*Acona*	117
1971	October	7	T, S, O_2, N	*Acona*	123
1971	December	4	T, S, O_2, N	*Acona*	125
1972	March	58	T, S, O_2, N	*Acona*	129
1972	April	6	T, S, O_2, N	*Acona*	131
1972	June	22	T, S	*Acona*	137
1972	September	33	T, S, O_2, N	*Acona*	141
1972	December	39	T, S, O_2	*Acona*	147
1973	January	16	T, S, O_2	*Acona*	153
1973	March	24	T, S, O_2	*Acona*	159
1973	May	39	T, S, O_2	*Acona*	164
1973	September	1	T, S	*Acona*	177
1973	October	4	T, S	*Acona*	181
1974	May	14	T, S	*Acona*	188
1974	July	1	T, S	*Acona*	193

TABLE 1 (Continued)

Year	Month	Number of Stations	Measurements	Ship	Cruise Number
1974	October	2	T, S	*Acona*	200
1974	November	1	T, S	*Acona*	202
1975	February	2	T, S	*Oceanographer*	805
1975	March	6	T, S, O_2, N	*Acona*	207
1975	April	3	T, S	*Rainer*	806
1975	June	2	T, S	*Acona*	212
1975	September	7	T, S	*Silas Bent*	811
1975	November	7	T, S	*Surveyor*	814
1975	December	2	T, S	*Discoverer*	816
1976	March	-	T, S, O_2, N	*Acona*	225
1976	June	-	T, S, O_2, N	*Acona*	229

NOTE: Symbols used to indicate the type of measurements made are the following:

T - temperature

S - salinity

O_2 - dissolved oxygen

N - nutrients

TABLE 2

SUMMARY OF DATA COLLECTED FROM GAK SEWARD LINE

Year	Month	Number of Stations	Measure-ments	Ship	Cruise Number
1970	December	11	T, S, O_2	*Acona*	109
1971	March	4	T, S, O_2	*Acona*	111
1971	July	11+	T, S, O_2	*Acona*	116
1971	September	11	T, S, O_2	*Acona*	120
1971	October	4	T, S, O_2	*Acona*	124
1972	April	7+	T, S, O_2	*Acona*	130
1972	June	11+	T, S, O_2	*Acona*	135
1972	October	9	T, S, O_2	*Acona*	144
1972	November	1	T, S, O_2, N	*Acona*	146
1972	December	1	T, S, O_2	*Acona*	148
1973	February	1	T, S, O_2	*Acona*	154
1973	March	1	T, S, O_2	*Acona*	160
1973	April	1	T, S, O_2	*Acona*	161
1973	May	1	T, S, O_2	*Acona*	166
1973	September	1	T, S, O_2	*Acona*	176
1973	October	1	T, S, O_2	*Acona*	180
1973	December	1	T, S, O_2	*Acona*	183
1974	March	1	T, S, O_2	*Acona*	186
1974	April	1	T, S, O_2	*Acona*	187

TABLE 3

SUMMARY OF CRUISES TO THE GULF OF ALASKA

Year	Month	Ship	Cruise Number
1974	July	*Acona*	193
1974	October	*Acona*	200
1974	November	*Acona*	202
1975	January/February	*Acona*	205
1975	February	*Oceanographer*	805
1975	March	*Acona*	207
1975	April/May	*Rainer*	806
1975	June	*Acona*	212
1975	August/September	*Silas Bent*	811
1975	November	*Surveyor*	814
1975	December	*Discoverer*	816

the station names and locations. Appendix B summarizes the type of data collected in the Sound.

2.2. Hydrographic Data

Temperature and salinity measurements were made at standard Prince William Sound and Gulf of Alaska stations during the 1971 to 1975 period using a Bissett-Berman (Plessey) Model 9040 salinity/temperature/depth measuring unit (STD). Nansen bottle samples were used for calibration at frequent intervals. Measurements of surface water temperatures were made using a thermometer and bucket samples.

Analog output from the STD were obtained in the form of charts showing continuous traces of temperature and salinity against depth. Simultaneously, these measurements were recorded in digital form on magnetic tape at 0.2 second intervals (about every 10 cm) during lowering of the STD.

Temperatures were measured at standard depths during Nansen casts with two protected reversing thermometers. Salinities of samples drawn from the Nansen bottles were determined using a Bissett-Berman Model 6220 or 6230 Portable Laboratory Salinometer. Temperature measurements from unprotected reversing thermometers were used in conjunction with those from protected reversing thermometers to determine the thermometric depths below 200 m.

The accuracy of the temperature and salinity measurements using the STD were estimated to be within ± 0.05°C and ± 0.05 ‰ respectively. However, measurements from the Nansen casts were estimated to be accurate to ± 0.02°C and ± 0.03 ‰. Surface temperatures from the bucket thermometer were accurate only to ± 0.1°C. The STD data were adjusted by comparison with the Nansen bottle data.

At some stations, Nansen samples were analyzed for dissolved oxygen using a modified Winkler technique and nutrients using an autoanalyzer. The accuracy of dissolved oxygen determinations was estimated to be ± 0.25 ml/l (Carpenter, 1965) and of nutrients to be approximately 15% (Nebert, personal communication).

Raw data are too voluminous for inclusion in this work. However, the Prince William Sound and Port Valdez data are available from the National Oceanographic Data Center. This data has been presented graphically and discussed by Muench and Nebert (1973) and Muench and Schmidt (1975). Data from the Gulf has been discussed by Royer (1975).

2.3. Weather Data

Weather data are not available from the central portion of the Sound at this time. However, weather stations are located at Cape Hinchinbrook, Cordova, Latouche, Valdez and Whittier (Fig. 2). The weather data from these stations are presented as monthly means in Appendix C. Summaries of wind data for ten years or more are available for Cordova, Valdez and Whittier with three years of data available for Cape Hinchinbrook (Muench and Schmidt, 1975). These wind data are probably not representative of conditions in the central Sound. The deep, narrow fjord valleys accelerate the winds producing narrow bands of wind that can extend for several miles outside (Searby, 1969).

The meteorological conditions over the Gulf of Alaska are better understood than over Prince William Sound. The weather regime in the region is controlled by the relative positions of the Aleutian Low and North Pacific High (Royer, 1975). Weather stations are located at Kodiak, Seward, Middleton Island, Cape St. Elias, Yakataga, Yakutat and Cape Spencer. Atmospheric data are used by Bakun (1973, 1975) to calculate upwelling indices based on Ekman surface wind transport.

2.4. Tide Predictions

The tides of Port Valdez and Prince William Sound are reported as mixed, predominantly semi-diurnal (Mungall, 1973). Tide and Tidal Current Tables are available for subordinate stations in the Sound (U.S. Dept. of Commerce) with all predictions being based on the reference station at Cordova. The tides are observed to range from 3 to 4 m. The shape of the basin may amplify the recorded or predicted tides for the towns and harbors located in the peripheral fjords. The effect of winds, changes in the atmospheric pressure and storms in the Gulf of Alaska will alter the predicted tides. Actual measurements of the tidal ranges and tidal currents in the Sound are not available. However, beginning in May of 1976 a Tide and Current Survey of Prince William Sound (National Ocean Survey, OPR-518-MA-76) will be conducted to update tide predictions (Muirhead, personal communications).

2.5. Bathymetric Information

Several sources of information on the bathymetry of Prince William Sound are available. National Ocean Survey Charts 16701, 16705, 16708, 16709 and 16700 (formerly C. & G. S. 8515, 8517, 8519, 8520 and 8551) provide a large number of soundings and indicate the general bottom topography. The seismic profiling work of von Huene (1967) provides a continuous north-south longitudinal trace of the bottom from Port Valdez through the central Sound to Hinchinbrook Entrance. Fathometer traces (12 kHz and 3.5 kHz) of the central Sound were made during a recent cruise (*Silas Bent*, 1975). Data from these sources are used to contour the bottom topography (Fig. 5), and draw a longitudinal section showing the basin shape and sill location (Fig. 6).

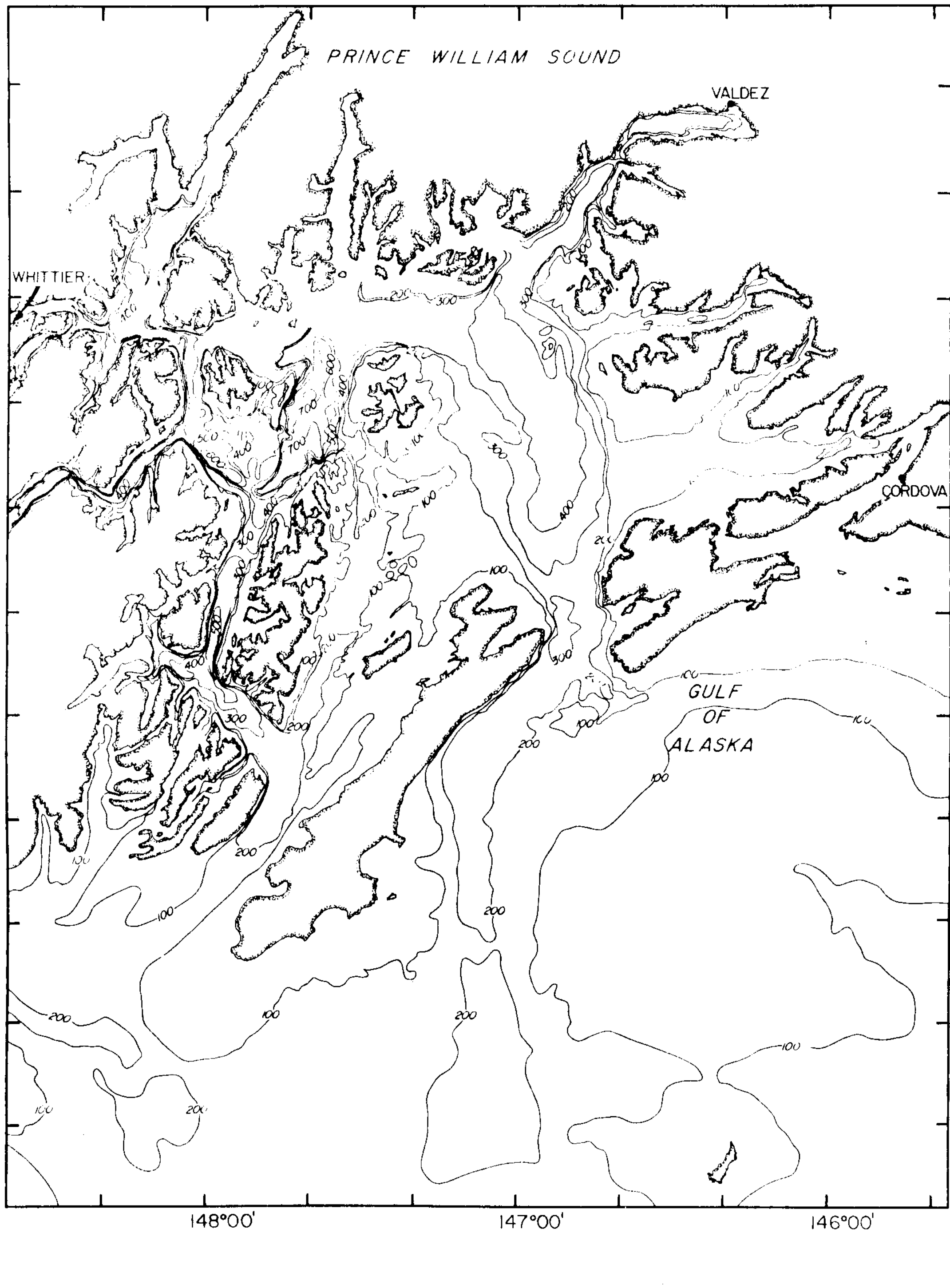

Figure 5. Bathymetry of Prince William Sound (depths in meters).

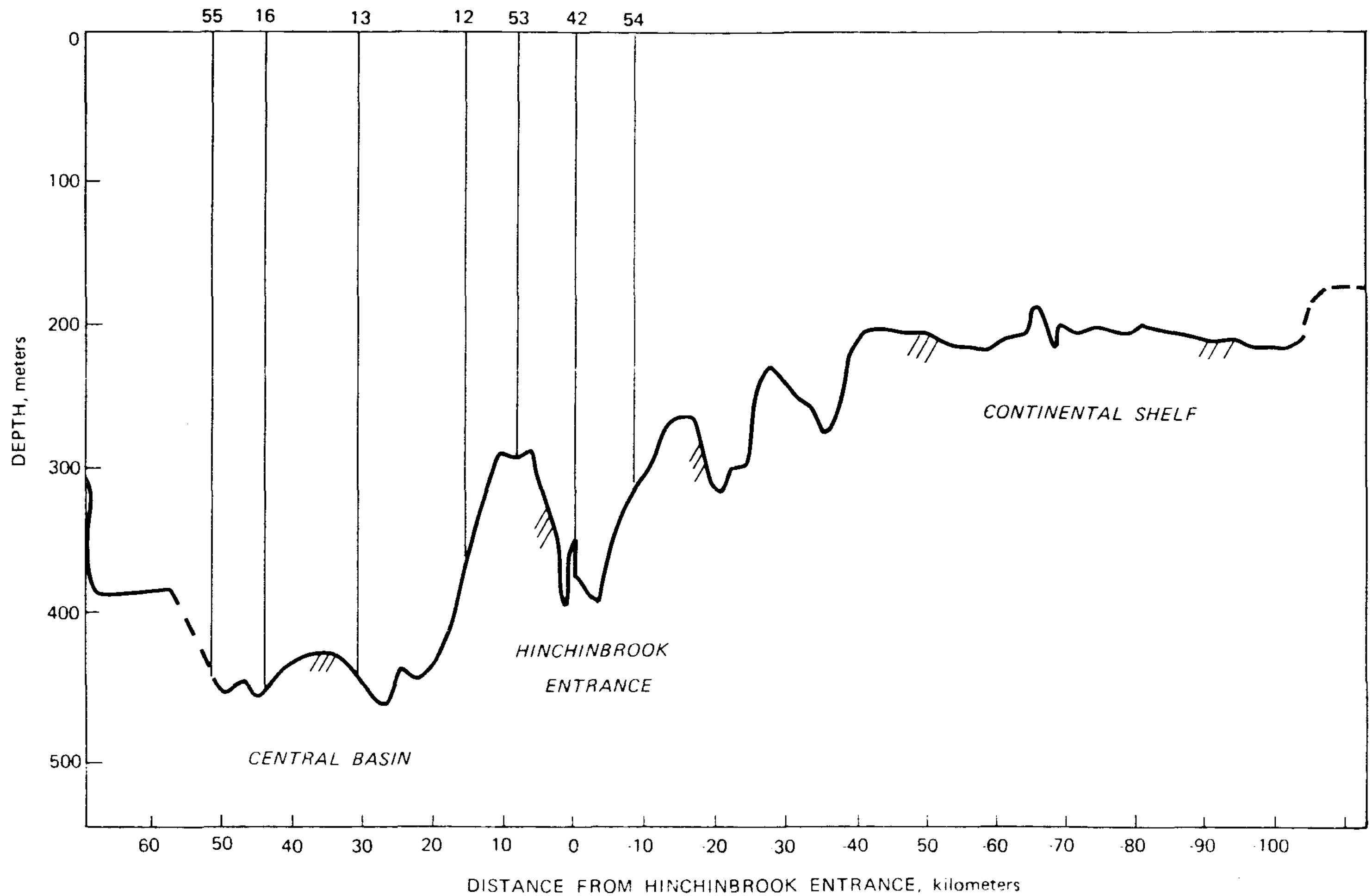

Figure 6. Longitudinal profile of Prince William Sound along the deepest continuous part of the basins.

3. PHYSIOGRAPHY

This is a description of the physical system given in preparation for the analysis of exchange processes in Prince William Sound. It consists of a description of the annual cycling of the hydrographic conditions in Prince William Sound and the Gulf of Alaska, along with the bathymetry of the system which contains these waters.

3.1. The Basin

Pritchard's (1952) topographic classification of estuaries emphasises the importance of basin configuration to physical processes in an estuarine system. An unusual configuration exists in Prince William Sound resulting from a combination of preglacial erosion, glacial excavation and tectonism acting at the intersection of two coastal mountain chains. A broad central basin, 100 km wide, surrounded by fjords, smaller bays and numerous islands constitutes the system. Free connection with the Gulf of Alaska exists through Hinchinbrook Entrance and Montague Strait, with limited access through the smaller islands and passes at the east and west. The large breadth of the Sound and multiple connections with the Gulf are pecularities which might distort a classical fjord-type circulation.

Figure 5 shows the complexity and irregularity of the bathymetry of Prince William Sound. The fjords and bays surrounding the central basin vary considerably in basin and sill depth. On the eastern side of the Sound there is a broad north-south basin over 400 m deep. To the west, separated from the central basin by Knight and Naked Islands there are a series of trenches 500 to 600 m deep with an 800 m deep hole located off Lone Island.

Access to the central basin exists principally through Hinchinbrook Entrance and Montague Strait. A channel over 200 m deep runs south from this basin through Hinchinbrook Entrance and over the continental shelf. Figure 2 shows a 400 m hole in Hinchinbrook Entrance and a 180 m saddle 37 km to the south. East of Hinchinbrook Entrance there is a 100 m channel paralleling the Gulf coast which connects with the 200 m channel at Seal Rocks (Fig. 5). Access through Montague Strait is considerably restricted compared to Hinchinbrook Entrance. A 200 m channel in Montague Strait shoals to 100 m as it approaches the continental shelf in the south and Green Island in the north.

Multiple access to the central basin of the Sound certainly exists; however, the effective sill depth (Saelen, 1967) or deepest connection between the fjord basin and outside ocean water is the determining bathymetric feature in deep water exchange. The effective sill for Prince William Sound is defined as the 180 m saddle located 37 km south of Hinchinbrook Entrance on the continental shelf. This location outside the fjord is not particularly unusual, as the sill depth for several Norwegian fjords is determined by the outlying coastal banks (Saelen, 1967). Based on the effective sill depth and Figure 5, a simplified model of the bathymetry is proposed. The 450 m deep basin connects with the shelf break primarily through the 100 m and 200 m channels that converge on Hinchinbrook Entrance at Seal Rocks. Essentially, then, the continental shelf forms a broad barrier between the Sound's basin and the oceanic source water.

3.2. The Fjord

As Section 2.1 shows, hydrographic data are available for Prince William Sound from 1971 to 1976 (Table 1). Even though the sampling interval is irregular, it is possible to construct a time series of temperature, salinity and density (σ_t) (Fig. 7) at PWS 13 (formerly station 2) in the central Sound. This time series shows a number of regular annual features which vary only in degree from year to year. Based on this, an annual hydrographic cycle is postulated with anomalous features discussed where appropriate.

Spring is a transitional period between the seasonal hydrographic extremes of winter and late summer. During this season, solar warming and freshwater input from snowmelt start to increase the stratification of the well mixed 50 m upper layer (Fig. 8). The surface temperature increases from a winter minimum (2° to 3°C) while salinity decreases from a winter maximum (over 32 °/₀₀, σ_t > 25.5). By summer, the stratification increases significantly in the upper 100 m with temperatures over 10°C and salinities from 27 to 28 °/₀₀. In the intermediate water (Sect. 1.4), there is a general tendency for slight cooling and freshening during spring along with a decrease in the vertical gradients of temperature and salinity. However, from year to year (Fig. 7) the temperature and salinity range (4° to 2°C and 32.5 to 32.1 °/₀₀) can vary. Temperature maxima occur between 75 and 100 m and might be indicative of advective inflows from the Gulf of Alaska (Sect. 4.3). The deep water (Sect. 1.4) is 1° to 2°C warmer than, but of similar salinity to the overlying intermediate water. This basin water is also cooling from its winter maximum with small changes in salinity.

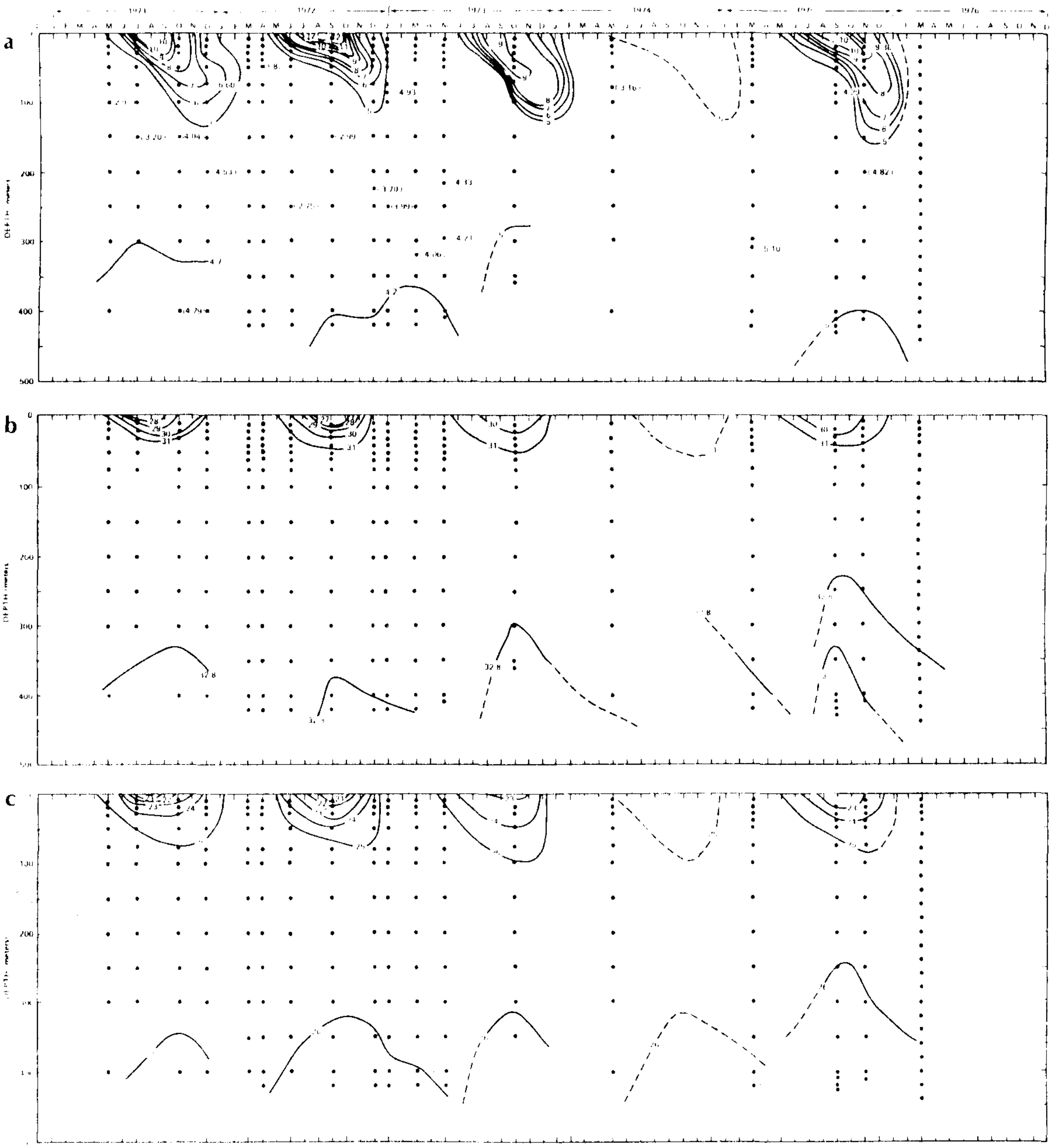

Figure 7. Time series of temperature, salinity and σ_t (density) for PWS 13 in Prince William Sound.

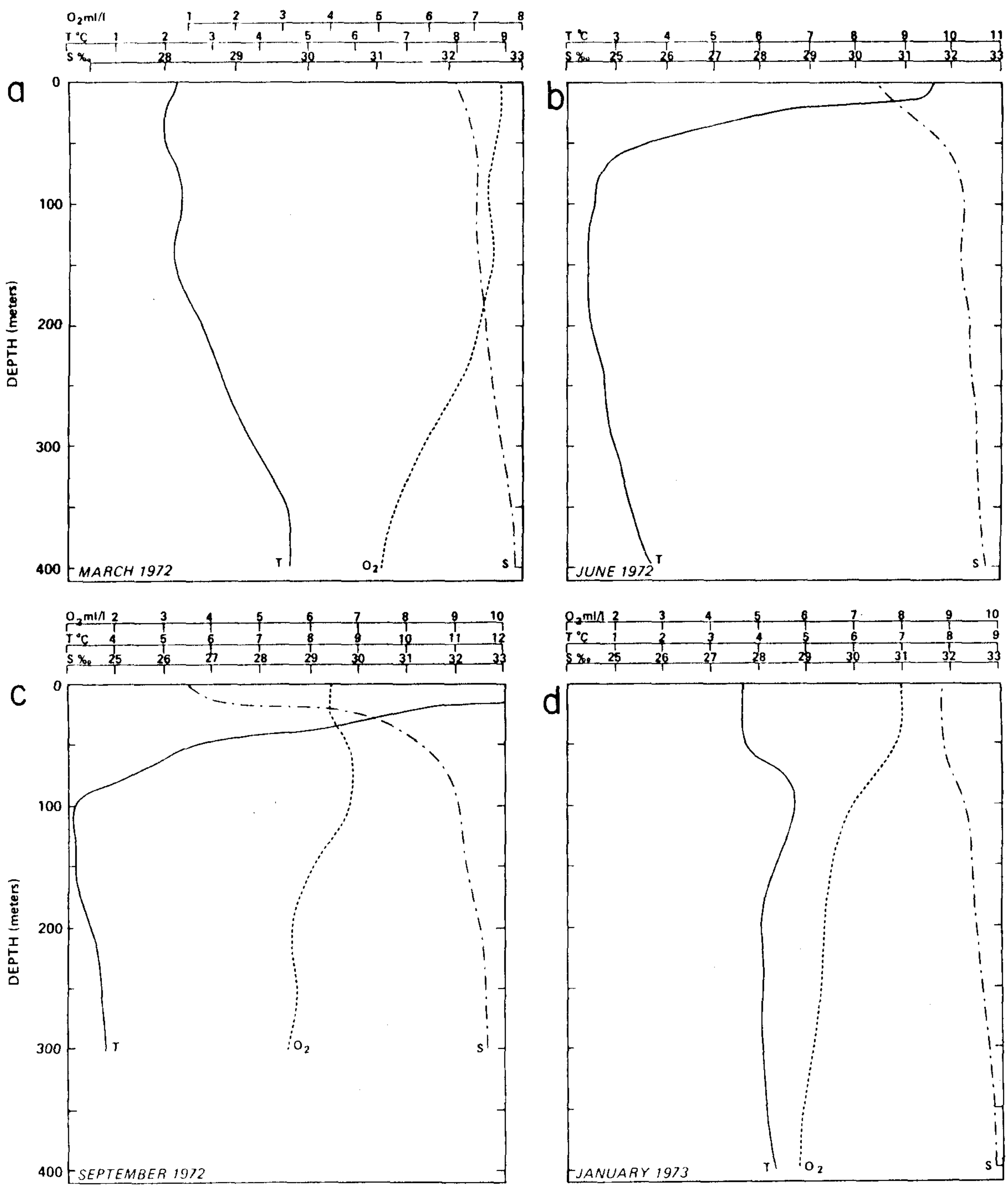

Figure 8. Vertical profiles of temperature, salinity and σ_t (density) at PWS 13.

During the late summer, the surface waters reach a temperature maximum and salinity minimum while the deep water reaches its annual peak in salinity and undergoes significant warming. Temperatures reach a surface maximum of 10° to 12°C by September with a negative gradient down to 100 or 150 m where a minimum (3° to 4°C) occurs (Fig. 8). Surface salinities reach a minimum of about 26 °/₀₀ with a positive vertical gradient down to 75 to 100 m where the gradient relaxes (Fig. 8). Below the highly stratified surface layer, the intermediate water is nearly isothermal and isohaline with depth. As opposed to the spring cooling and freshening, the intermediate water seems to be warming (about 1°C) and increasing in salinity (about 0.2 °/₀₀) with variations in the extent from year to year (Fig. 7). By the summer, the spring temperature maxima are located lower in the water column. The deep water increases in both temperature and salinity throughout the summer, reaching a temperature maximum (4° to 5°C) and salinity maximum (32.8 to 32.9 °/₀₀, σ_t = 26) by September or October. An anomalous situation existed in September of 1975 where the deep water was warmer (5°C) and of higher salinity (33 °/₀₀) than in previous years.

As in the spring, autumn is a time of gradual transition between the extremes of oceanographic summer and winter. Stratification in the surface water decreases throughout autumn from a maximum in late summer (Fig. 8). As the surface water cools, a subsurface temperature maximum layer (6° to 9°C) develops from 30 to 75 m depending on the time of year. From this subsurface maximum, the temperature decreases down to a minimum layer (from 3.5° to 4.5°C) at about 200 m (Fig. 8). The surface waters are isohaline to the depth of the mixed layer, below which the salinity increases uniformly to the deep water (Fig. 8). The limited autumn data do not show any temperature maxima or small scale features in the intermediate water. From the 200 m temperature minimum layer, both the temperature and salinity gradually increase into the deep water. The deep water gradually decreases in salinity but continues to increase in temperature throughout autumn into winter.

By the end of winter, near surface water stratification is minimal while the deep water begins a warming trend, but continues to freshen. Surface temperatures reach a minimum of 2° to 3°C (0.5°C in March, 1972) along with a salinity maximum over 32 °/₀₀ by spring (Fig. 7). A vertically homogeneous layer develops from the surface down to about 50 m probably resulting from wind and thermohaline convective mixing (Fig. 8). Below the mixed layer, the temperature increases to a deep (200 m) temperature maximum, then decreases to a minimum at 300 m. There is only a small positive salinity gradient through this layer (Fig. 8). The intermediate water generally continues to warm during the winter as in the summer and autumn, but starts to freshen continuing into summer. The deep water continues to decrease in salinity (Fig. 7) reaching a minimum by late winter and early spring. Temperature data are irregular, but in 1973 the deep water warmed to a maximum in February while in 1975 it peaked in October, decreasing by February. This may be related to the extent of vertical mixing discussed in Section 4.5.

Superimposed on this annual hydrographic cycle is an intermittent doming of the isopleths of temperature, salinity and density (σ_t) (Muench and Schmidt, 1975). As more data accumulate, this feature seems to appear at all seasons of the year, being more pronounced during the winter. These features suggest that a cyclonic circulation regime may occur in the central Sound.

Clearly, considerable variability exists from year to year, however these general trends seem to occur annually. The surface waters appear to respond largely to seasonal heating, cooling and freshwater input, while the deep and intermediate water seem to follow seasonal cycling on the continental shelf. Significant short term fluctuations probably occur, but the large sampling interval does not show these.

3.3. The Ocean

The northern continental shelf of the Gulf of Alaska provides the oceanic source water for deep water exchange in Prince William Sound. The oceanographic data from this area give evidence for the annual cycling of water mass characteristics and the general circulation regime.

Seasonal variations in the surface waters of the Gulf depend on winter cooling, summer heating and freshwater input from the coast (Royer, 1975). By spring, the surface waters cool to a minimum of about 2°C while salinity and density reach a maximum (32 ‰, $\sigma_t = 26$). From the surface down to 80 or 100 m, a well-mixed layer develops during the winter. Below this mixed layer, a temperature minimum occurs from which the temperature increases uniformly to the bottom (>5°C). Salinity and density also increase uniformly from the mixed layer to the bottom (32.6 ‰, $\sigma_t = 26$). Considerable surface stratification develops throughout the summer from solar warming and freshwater input from the Copper River and snowmelt along the coast. Surface temperatures reach a maximum (11 to 13°C) by September while salinity and density approach a minimum (25 $^{\circ}/_{\circ\circ}$, σ_t = 23). The sharp surface gradients extend to about 60 m, below which the temperature decreases while the salinity increases.

Annual cycling of the bottom waters on the Gulf of Alaska shelf depend on seasonal variations in the meteorological regime (Royer, 1975). The meteorological regime of this region is controlled by the relative positions of the Aleutian Low and North Pacific High (Fig. 9). Dominance of the Aleutian Low brings a series of severe storms and strong easterly winds during the winter, while the Pacific High normally dominates during the summer and is accompanied by relatively fair weather and a weak reversal in the wind regime. Bakun (1973) and Ingraham *et al.* (1976) use sea level pressure data to calculate time series of wind stress and resultant Ekman transports for the northern Gulf. These calculations and the observed weather regime indicate intense coastal convergence and subsequent downwelling during the winter. This would cause low density surface waters to pile up along the coast, forcing the warm (4 to 5°C), high salinity (32.8 to 33.0 $^{\circ}/_{\circ\circ}$) deep water off the shelf and replacing it with cold (3°C), low salinity (32.5 $^{\circ}/_{\circ\circ}$) water (Fig. 3). The wind stress transport calculations also show a summer relaxation and shift to a weaker, more stable coastal divergence at the surface. This would allow warm, high salinity water to move up onto the shelf from the central Gulf (Royer, 1975). Bakun's (1973) time series of upwelling indices (Fig. 3) shows the seasonal cycling of winter downwelling and summer upwelling. Ingraham *et al.* (1976) point out that extreme events are superimposed on this annual cycle, particularly during the winter.

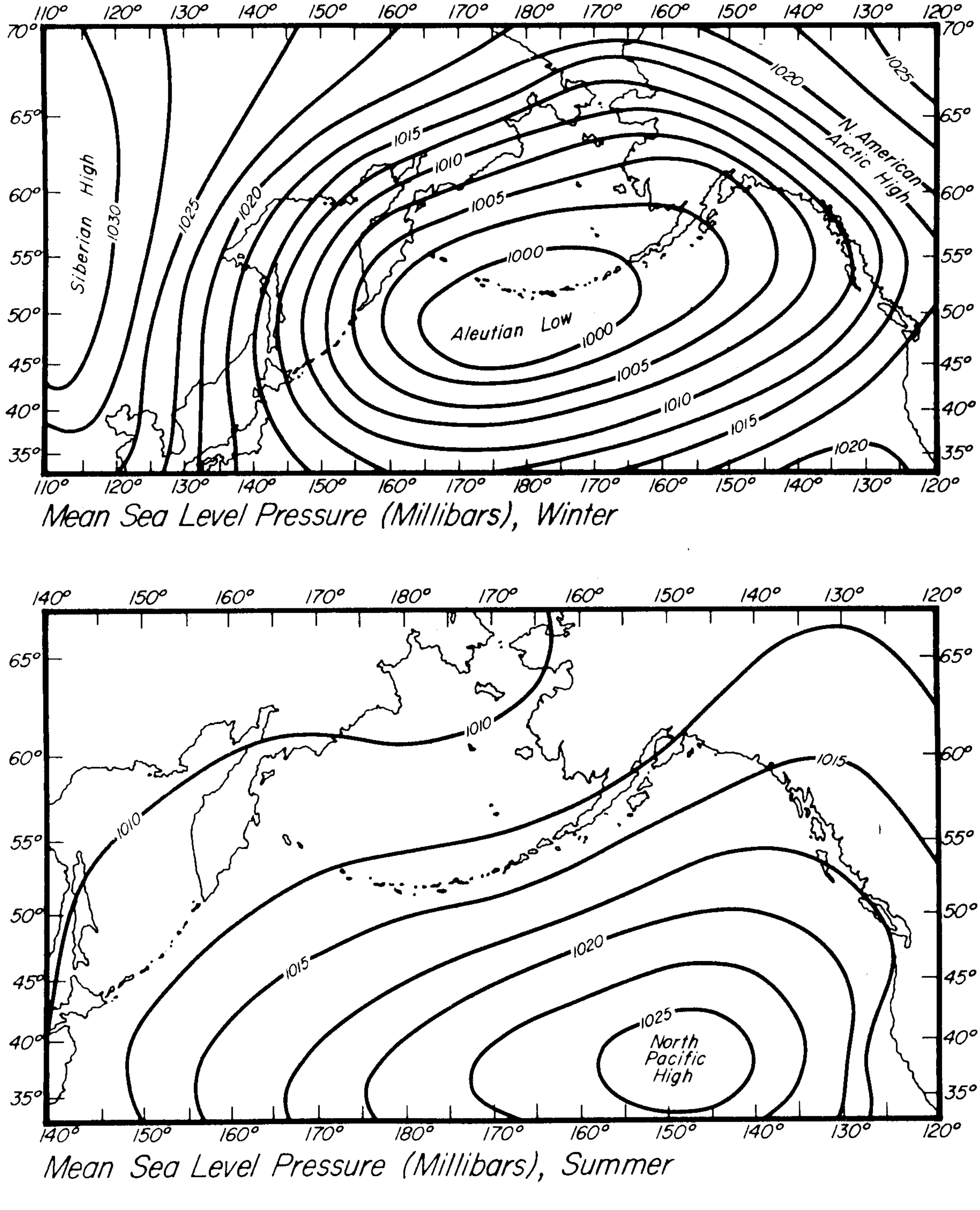

Figure 9. Mean atmospheric pressure distribution over the North Pacific for winter and summer (after Dodimead, Favorite and Hirano, 1963).

The circulation regime for the continental shelf between Seward and Yakutat is composed of a stable mean flow modified by seasonal and small scale variations (Galt and Royer, 1976). The mean flow is westerly (Dodimead *et al.*, 1963) with the Alaska Stream dominating. There is also a tendency to follow the bottom topography with the current on the surface being stronger than on the bottom. Galt and Royer (1976) observed warm and cold water cores or filaments which support the concept of a westerly flow. During the winter, the westerly flow accelerates while during the summer it relaxes. This is probably caused by the annual cycles of wind stress and onshore-offshore transport which piles up water along the coast, accelerating the westerly barotropic component. In addition to seasonal variations, small scale and short-term variations such as tides, individual storms and internal waves could considerably modify the mean flow.

4. EXCHANGE

An exchange mechanism for Prince William Sound is proposed, consisting of advective inflow plus diffusive mixing (Sect. 1.4). The nature of the marine source water and the manner in which it is presented to the Sound is considered first. The inflow of source water through Hinchinbrook Entrance is then examined. Advective influx and exchange are analyzed in both the intermediate and deep fjord water. Finally, vertical eddy diffusion between the deep and intermediate fjord water is considered. From this, it is hoped to gain some understanding of the duration, extent, frequency, and regularity of exchange.

4.1 Oceanic Source Water

The mean westerly flow of the Alaska Stream follows the coast from Yakutat to Kayak Island (Sect. 3.3). However, the flow separates from shore at Kayak Island and bifucates over the broad shelf, flowing southwest and northwest (Royer, personal communication). This leaves the broad, shallow shelf in front of Prince William Sound somewhat removed from the influence of the mean westerly flow that dominates over the rest of the Gulf. It is this area that provides source water to Prince William Sound.

Circulation along the coast from the Copper River to Montague Strait is not as well understood as the mean westerly flow along the shelf break. However, beginning in 1974, hydrographic data (Table 3) and current measurements are available giving some insight into the nature of the circulation. The general circulation remains westerly, but weaker and more variable (Galt and Royer, 1975) with the irregular bathymetry

(Fig. 10) tending to channel the flow. Winter intensification of the westerly flow and short term responses to storms seem to occur here as in the main Gulf circulation. Current meter measurements at GASS 60 (60°01.5'N, 145°51.2'W) show that the near surface flow is stronger than the near bottom flow (Galt and Royer, 1975). In addition to the westerly flow, two small gyres have been observed and modeled (Galt, 1975, 1976) south of the Copper River which seem to be related to freshwater input from the Copper River. These current measurements along with satellite photos and sediment accumulation in Orca Inlet all suggest a westerly flow along the 100 m channel (Sect. 3.1) presenting ocean water to Hinchinbrook Entrance at Seal Rocks. This would seem to be a primary mechanism for presenting oceanic source water to Prince William Sound.

Seasonal cycling in the water mass characteristics of this source water can be described for 1974 and 1975 at GASS 54 (60°13.9'N, 146°48.6'W) located just south of Hinchinbrook Entrance (Fig. 4). Variations in the surface waters seem to depend on winter cooling and summer heating as described by Royer (1975) for GAK 1 (Fig. 4). By spring, the surface water cools to less than 3°C while salinity and density reach a maximum (> 31.5 °/₀₀, > σ_t = 24.8) (Fig. 11). A well mixed layer develops down to 80 or 100 m, below which the temperature, salinity and density all increase uniformly to the bottom. During summer, the surface waters become increasingly stratified from solar warming and freshwater input, especially from the Copper River. Surface temperatures reach a maximum of over 12°C while salinity decreases to 28 °/₀₀ (σ_t = 22) by autumn (Fig. 11). Stratification increases until it reaches down to 60 to 80 m. The bottom waters outside Hinchinbrook Entrance appear to

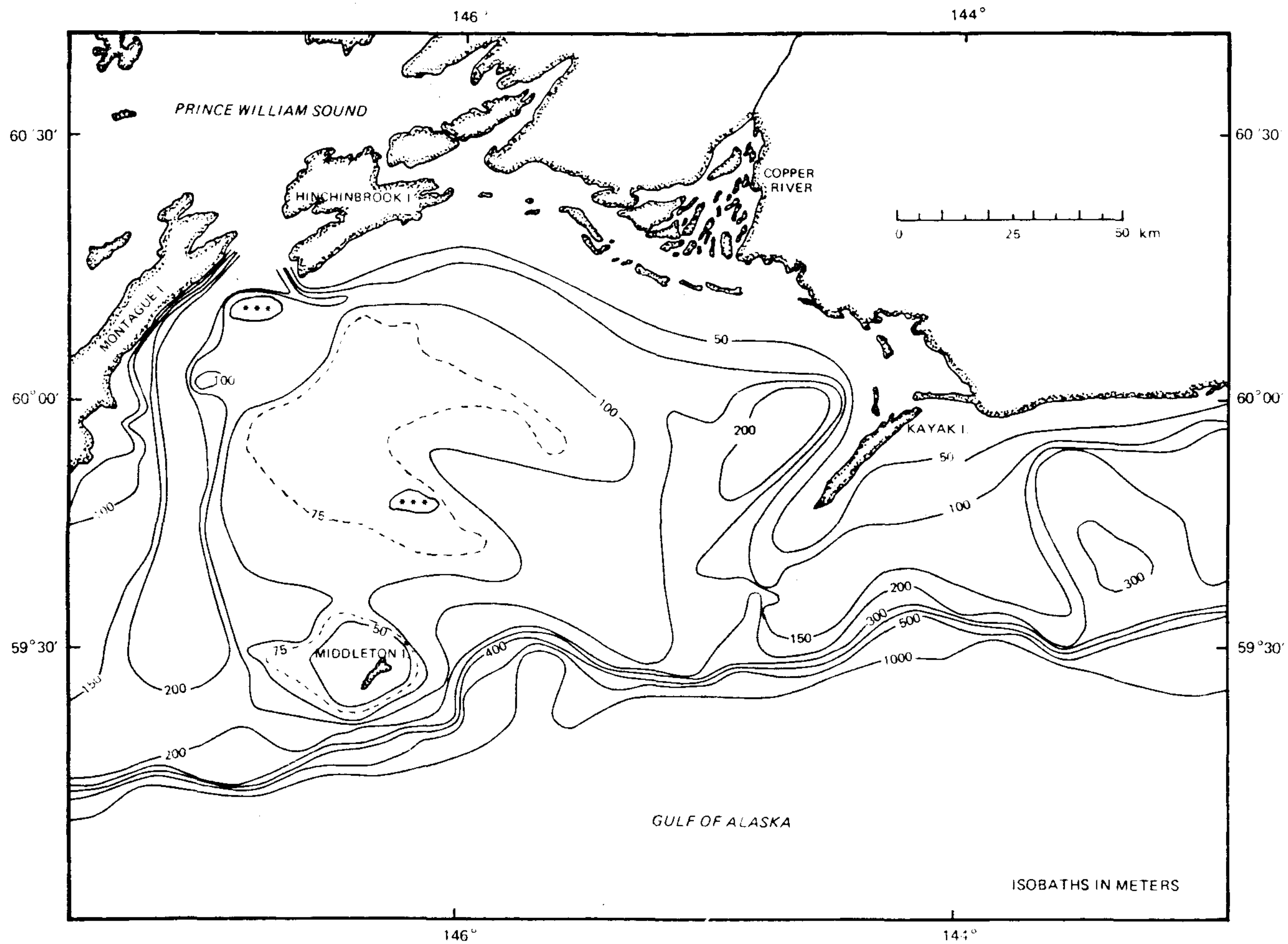

Figure 10. Bathymetry of the Gulf of Alaska shelf off Prince William Sound (depth in meters) (Worley).

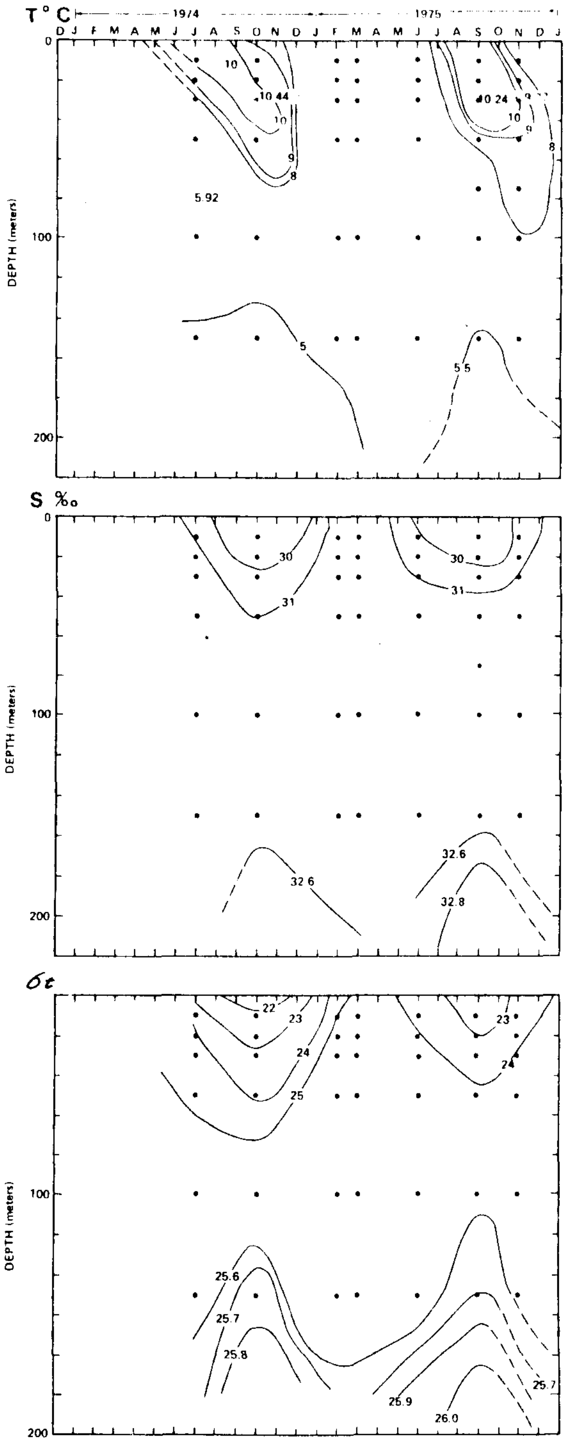

Figure 11. Time series of temperature, salinity and σ_t (density) at GASS 54 outside Hinchinbrook Entrance.

follow a seasonal cycle (Sect. 3.3) similar to GASS 1 (Fig. 4). Warm (5°C) high salinity (32.6 to 32.8 °/₀₀ at 200 m) water appears during the summer (Fig. 11), reaching its maximum by late summer or early autumn.

GASS 54 (Fig. 4) is located behind the effective sill in a deep channel running north from the shelf break through Hinchinbrook Entrance (Sect 3.1). This station is in 200 m of water while the deepest continuous part of the channel at this point (Fig. 5) is over 250 m. Hydrographic data to describe the source water presented below 200 m at Hinchinbrook Entrance are not available, but if GASS 54 were located in deep water, the autumn bottom water density maximum would probably be larger than that presently observed. Deep waters (> 200 m) at both GASS 1 (Royer, 1975) and PWS 42 and 12 (Muench and Schmidt, 1975) (Fig. 4) are of higher salinity throughout the year than the deepest water (200 m) at GASS 54. Because of this, it is assumed that deep water (200 m to the bottom) outside Hinchinbrook Entrance might reach a density maximum between 32.6 and 33.5 °/₀₀ (maximum for GASS 1, Fig. 3). The presence of high salinity water at GASS 54 seems reasonable, but the magnitude of the maximum probably varies significantly from year to year. This is expected since the bottom water density maxima inside Resurrection Bay are consistently higher than those for Prince William Sound.

The nature of the source water at GASS 54 gives some indication of the manner in which it is presented to the fjord. During 1974 and 1975, the near bottom water in the 100 m channel east of Hinchinbrook Entrance (GASS 51) was of lower salinity than the bottom water at GASS 53 and 54 (Fig. 12). It seems possible that surface and intermediate water is advected to Hinchinbrook Entrance by the westerly flow along this 100 m

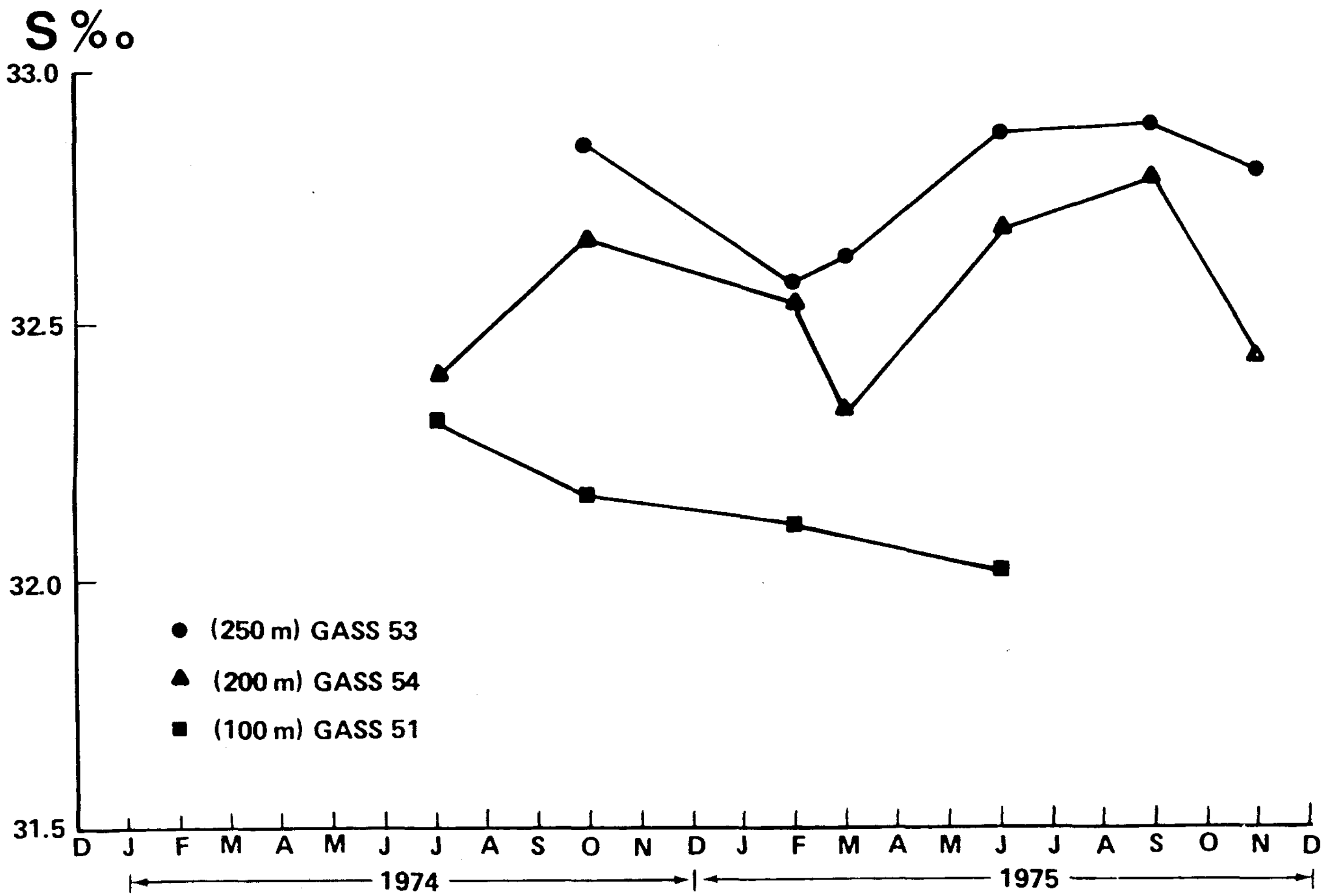

Figure 12. Salinity variations at GASS 51, GASS 53, and GASS 54 in the Hinchinbrook Entrance region.

channel. However, this mechanism does not explain the presence of high salinity deep water (100 to 300 m) at GASS 54 and inside Prince William Sound. The most reasonable mechanism for this seems to be an onshore flow along the 200 m channel into Hinchinbrook Entrance. This would be the most direct path for high salinity water to gain access to Hinchinbrook Entrance.

The proposed source water for Prince William Sound is a combination of shelf water flowing westerly along the 100 m channel and water from the shelf break which might move through the 200 m channel, over the effective sill (180 m) and down into the deep troughs at Hinchinbrook Entrance (Fig. 6). For 1974 and 1975 GASS 54 (Fig. 4) provides the best representation of the intermediate source water being presented through the 100 m channel. However, most of the data (Sect. 2.1) available for the fjord are from 1971 to 1973 while the Seward line is the only available ocean data. Comparison of T-S diagrams for the stations on the Seward line with GASS 54 indicates that the water mass characteristics for GASS 1 are similar to GASS 54 (Fig. 13). From 50 to 100 m the salinity at GASS 1 is consistently somewhat lower (0.1 to 0.2 $^\circ/_{\circ\circ}$) than at GASS 54 (Fig. 13). However, all the other Seward stations are higher in salinity than GASS 54. Therefore it will be assumed that GASS 1 is the best available representation of intermediate source water for 1971 to 1974. The deep source water moving down the 200 m channel is represented by GASS 59B (Fig. 4). This station is not in the 200 m channel, but it is just off the shelf break and slightly to the east. Of the available stations on the Hinchinbrook line, this is the only one over 200 m deep aside from GASS 54 and it seems reasonable to expect the

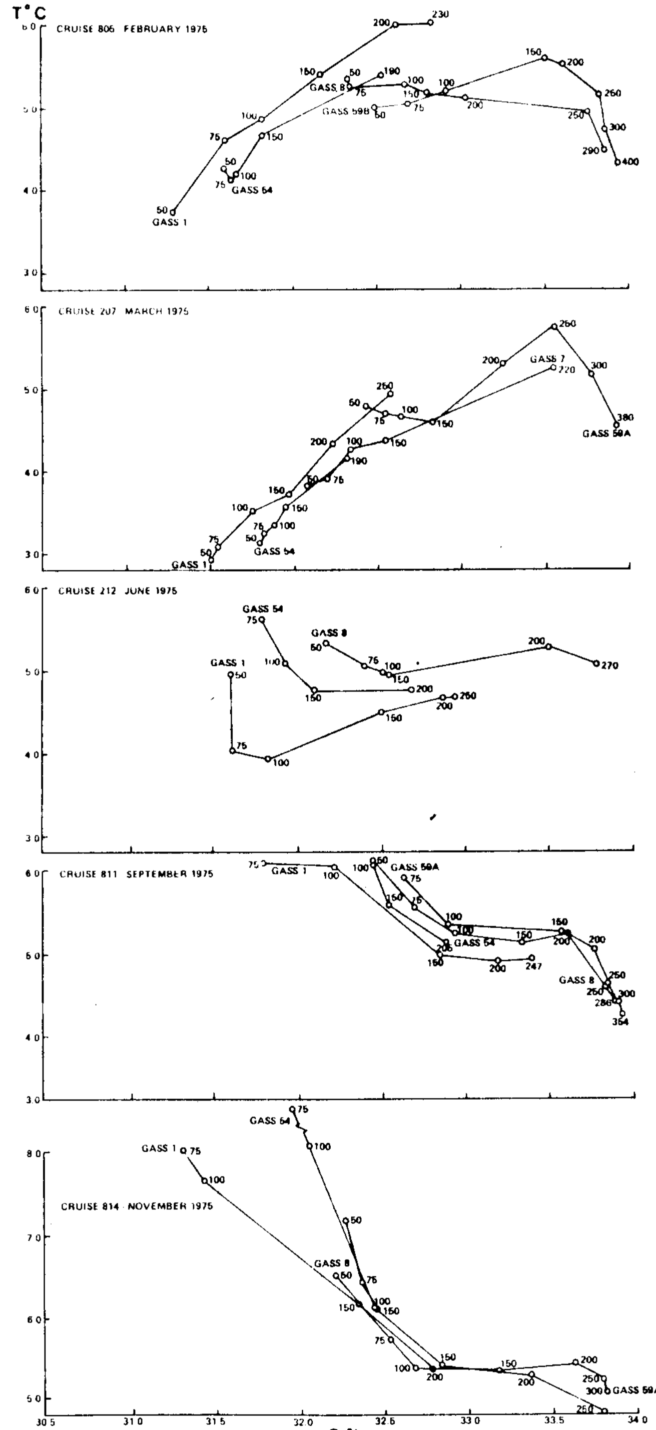

Figure 13. T-S diagrams for GASS 1, 8, 54, and 59B in the Gulf of Alaska.

westerly flow of the Alaska Stream to transport this water past the 200 m channel. Again, comparison of T-S diagrams (Fig. 13) indicate that GASS 8 on the Seward line has water mass characteristics most like GASS 59B. Therefore, GASS 8 is used during the 1971 to 1974 period when the Hinchinbrook line is not available. It is expected that considerable mixing takes place along the 200 m channel if inflow does occur.

4.2 Hinchinbrook Entrance Inflow

After the marine source water is presented outside the fjord, the inflow of this water over a sill or through a narrow strait or entrance can occur as deep water exchange. It is a complicated hydrodynamic problem which can vary considerably between fjords (Sect. 1.3). A combination of the density distribution, tides, wind and bathymetry can result in current profiles that may vary considerably.

Hinchinbrook Entrance is assumed to be the primary inlet for advective inflows to the deep basin of Prince William Sound (Sect. 3.1). This narrow entrance is about 12.1 km across with a complex bathymetry (Figs. 5 and 6). On the west side of the entrance there is a deep trough over 350 m deep, while on the east side the bottom rises to 200 m. The proposed inflow of source water through this entrance (Sect. 4.1) is a combination of shelf water from the east and deep water from the shelf break. Assuming that dense water moves along the 200 m channel and over the 180 m sill, it would follow the deepest continuous path into the Sound (Fig. 6), passing through a number of deep troughs over 300 m before it gains access to the 450 m central basin. Considerable mixing probably results from flow along such an irregular channel.

Annual cycling in the water mass characteristics of the ocean water (Sect. 3.3, Fig. 3) and the fjord water (Sect. 3.2, Fig. 7) shows when a density difference exists between the fjord and the ocean. This can indicate when advective inflow and subsequent exchange are possible. Comparison of the intermediate depth fjord and ocean water indicates that a density difference develops during spring, increases during summer and reaches a maximum by autumn (Fig. 14). Both the limited data at GASS 54 (Fig. 11) and the longer time series at GASS 1 (Fig. 3) indicate that this is the general situation. A density difference also develops between the fjord water and the deep ocean water at the shelf break (Fig. 14). This difference reaches a maximum in autumn as the intermediate water does. These seasonal changes in the density differences are expected as they coincide with the appearance of warm, high salinity water on the shelf during summer (Sect. 3.3). Based on these density differences, advective inflow and the subsequent exchange of fjord water increases in likelihood throughout the summer becoming most likely during autumn.

Direct current measurements are not available for Hinchinbrook Entrance, but hydrographic data and tide predictions (U.S. Dept. of Commerce, 1972-1973) are available. The limited hydrographic data show steeply sloping isotherms and isopycnals across the Entrance (PWS 42, 11, 43) which are not observed further into the Sound. The slopes of the isopleths vary considerably, ranging from positive through zero to negative, while at times they slope downward from each side of the channel to the center (Fig. 15). It is speculated that the large tidal prism of the Sound which funnels through Hinchinbrook Entrance may dominate the circulation at any particular observation. To investigate this,

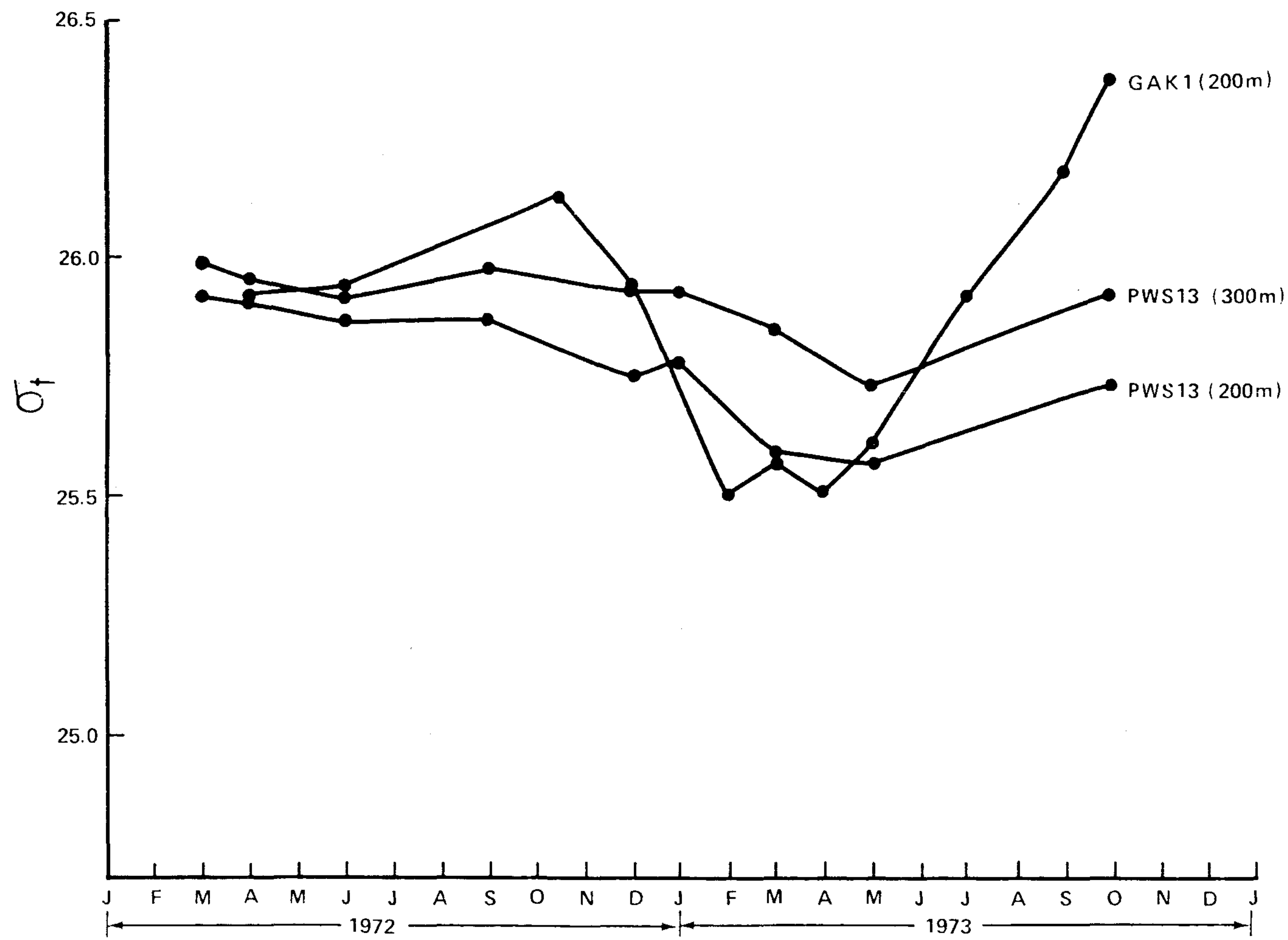

Figure 14. Density differences between GAK 1 and PWS 13.

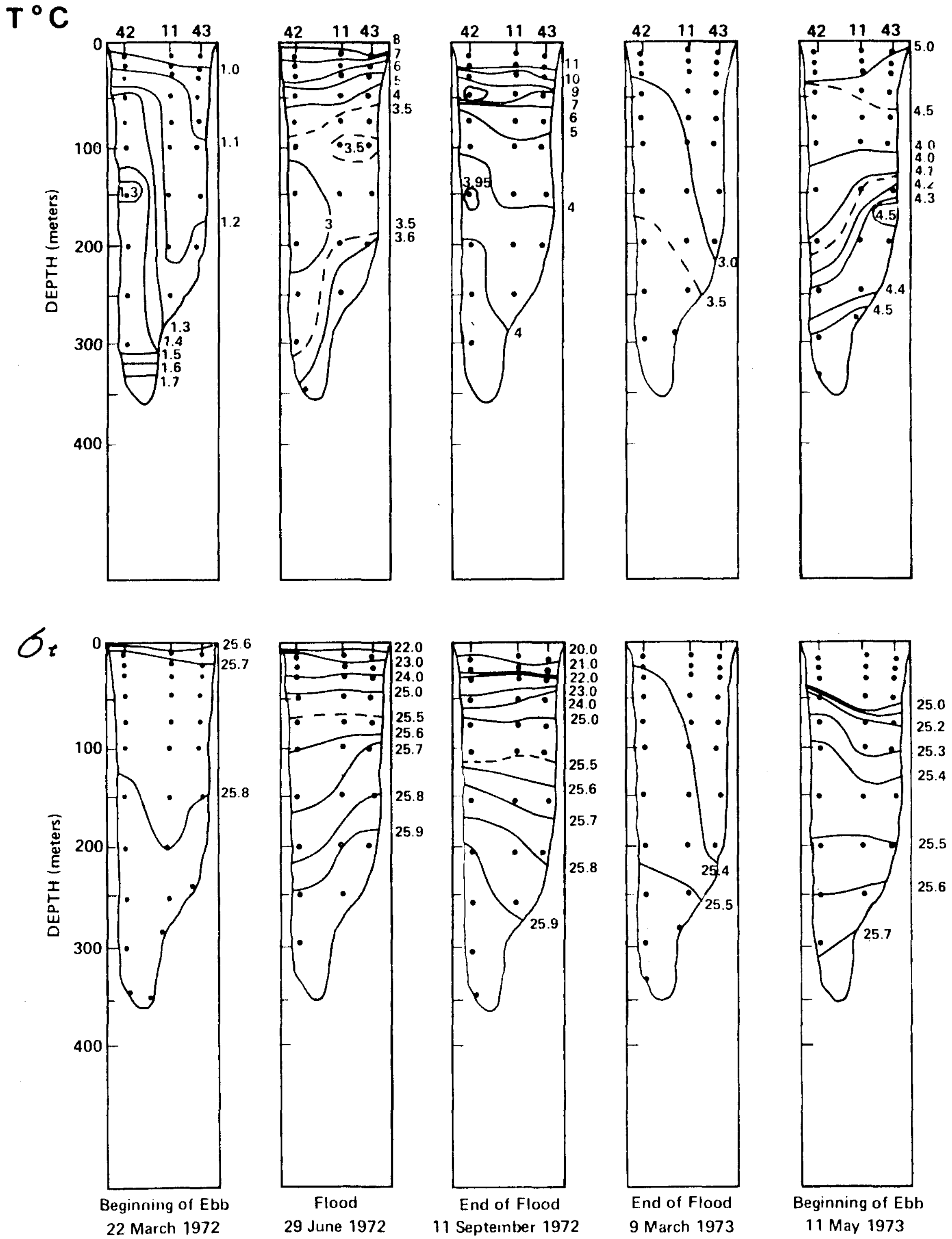

Figure 15. Temperature and σ_t (density) profiles across Hinchinbrook Entrance.

the predicted tides are compared with the observed hydrographic structure (Fig. 15). It is important to consider here that the predicted tides refer to conditions at the surface only and might not represent the stage of currents at depth. In most cases, this comparison shows that the isopycnals slope downward to the east during a predicted flood tide and to the west during a predicted ebb tide. In the case where the isopleths slope down from each side of the channel, a predicted ebb tide is just starting. A near surface outflow, along with a deep continuing inflow would agree with the predicted tides and account for the observed isopleths. Herlinveaux (1954) reports a two way flow in Juan de Fuca Strait where the outflow is longer and stronger at the surface, while the inflow is stronger at depth. These inflowing currents veer to the right of the channel as expected from the Coriolis force. The limited hydrographic data indicate that a flow regime somewhat like this might exist in Hinchinbrook Entrance. In addition to the tidal currents, meteorological tides, freshwater input and baroclinic components from the Gulf of Alaska will contribute to the inflow.

This type of tidally dominated flow through a narrow strait or entrance is discussed by Tully (1958) and Bowden (1967) for the Strait of Juan de Fuca. By assuming that acceleration and frictional terms are negligible compared with the Coriolis term, it is possible to apply the geostrophic approximation and calculate the velocity profile and transport. This dynamic method is an open ocean tool which must be used with caution in estuaries. Wilson (1975) has applied it to Long Island Sound by avoiding simplifying approximations and solving the equations numerically. However, Nutt and Coachman (1965) and Nebert and Matthews

(1972) have used the technique in fjord type estuaries. Nebert's detailed analysis of the method shows that a combination of bottom friction, choice of a reference level and station positioning introduced significant errors. Finally, a rigorous survey of measured and calculated currents (Forrester, 1970) in the St. Lawrence estuary confirms that the calculated currents do not agree with measured currents in a restricted channel. Because of this evidence, geostrophic currents and transport through Hinchinbrook Entrance are not presented. The long interval (2 to 3 hours) between casts in the Entrance may also distort the observed distribution of mass.

4.3. Intermediate Advective Exchange

Nutt and Coachman (1956) pointed out that advective exchange in a fjord-type estuary with a deep basin occurs in both the deep and intermediate water. Free horizontal exchange between the ocean water and the intermediate fjord water occurs primarily by tidal motions and density currents. This intrusion of ocean water into the fjord and subsequent exchange was considered in detail by Ebbesmeyer (1973). Ebbesmeyer identified and tracked medium scale water parcels ("boluses") of various sizes (10 to 100 m by several kilometers) as they moved into and around Dabob Bay, Washington. The thermal microstructure in the water column is used to locate local extrema, inversions and homogeneous regions separated by sharp gradients. Careful contouring of these features can indicate the presence of parcels covering several closely spaced stations. Using "NO" = 9 NO_3^- + O_2 (Broecker, 1974) as a conservative water mass tracer, Reeburgh *et al.* (1975) identified bolus type intrusions into Russel Fjord, Alaska. Ebbesymeyer pointed out that most bolus type intrusions are probably tide generated, interleafing with the fjord water at the appropriate density level. However, parcels larger than a tidal prism appeared suggesting that some mechanism, probably wind driven transport, supplements the tidal intrusion.

Seasonal variations in the hydrographic structure of Prince William Sound are described by Muench and Schmidt (1975) and reviewed in Section 3.2. The temperature structure follows the general trend of winter cooling and summer warming. However, local temperature extremes, inversions and homogeneous regions separated by sharp gradients are observed in the continuous vertical STD traces. Stations in Prince William Sound are from 5 to 15 km apart and are located along a north to south longitudinal section with lateral cross sections approximately 10 km apart (Fig. 4). Sections along these stations (Fig. A to U, Appendix D) show the presence of bolus type parcels. Contouring these complex features is certainly open to considerable individual interpretation, but they are contoured as medium scale parcels. It is necessary to contour temperature at 0.1°C intervals to show the detailed structure. In addition to temperature sections, sections showing NO values are used. Parcels or boluses observed in the Sound are described as to their size, depth and seasonality.

Boluses appeared in the intermediate fjord water in early spring. In March 1972 (Fig. E) the temperature structure was the most complicated of any observed in the Sound. An unusually severe winter (Royer, 1975) and the proposed counter clockwise gyre suggested by the doming isopleths could have been the cause of this complex structure. A tongue of warm

(1.5°C) water (Fig. E) appears to have moved in through Hinchinbrook Entrance. Under the 2°C dome there were two parcels between PWS 55 and 13 with warm cores at 150 m and 200 m. It is likely that the forces producing the dome also distort the shape and depth of these parcels. These parcels were also observed on the NO sections (Fig. NE). Boluses or warm cores were not present in March 1973 (Fig. K) which may indicate that the parcels are not advected in with each flood tide, or that they do not maintain their identity for very long as Ebbesmeyer found. However, in March of 1975 and 1976 (Fig. P and T) boluses with warm cores (> 3.5°C) were again observed at 75 m between PWS 55 and 13.

By April 1972 (Fig. F), the doming in the isotherms observed in March 1972 is considerably reduced, while a single large bolus with a warm core at 75 m between PWS 1 and 13 is observed. It is difficult to determine the size of this feature as the STD data for this cruise is widely spaced and there is insufficient nutrient data to contour a NO section. In May of 1971 and 1974 (Fig. A and M), STD data are not available and the Nansen data is not of sufficient detail to determine the thermal microstructure. STD data is available for May of 1973 (Fig. L) and temperature maxima (3.5 to 4.0°C) are observed at 100 m at PWS 13 and 42, but are small scale features observed at only one station.

During the early summer of 1972 (June, Fig. G), boluses appeared which were warmer, deeper and larger than those observed earlier in the year. Numerous temperature maxima (2.5 to 3.0°C) existed throughout the Sound between 100 and 200 m with parcels ranging in size from a few kilometers to 10 km or more. NO maxima (740 to 760 μg at/ℓ) also occured at 100 m (Fig. NG) coinciding with the temperature maxima (Fig. G). Very few data are available for June of 1975 (Fig. Q), but temperature maxima (> 5°C) do occur between 100 and 200 m just outside Hinchinbrook Entrance at GASS 54. Temperature maxima did not appear during June 1976 (Fig. U), instead a minima layer existed at 100 m throughout the central Sound.

By late summer or early autumn a well developed temperature minimum layer between 100 and 150 m existed throughout the Sound (Fig. C, H and R). Isolated temperature maxima and small scale parcels appeared in the Hinchinbrook Entrance area (PWS 12 to GASS 54) which were warmer and deeper than those observed during spring and summer. This is the season when warm, high salinity water appears on the continental shelf and the density difference between the source water and fjord water is greatest (Sect. 4.1). When these conditions exist, the appearance of warm, high salinity features deep in the water column at Hinchinbrook are expected. The absence of medium scale parcels in the intermediate water of the central Sound might indicate that the exchange is shifting to deeper advective intrusions associated with the source water density maximum occurring at this time of year.

Intermediate depth boluses did not appear during the winter months in the central Sound (Fig. D, I, J and S). Below a well mixed surface layer, the temperature of the intermediate water decreaseed to a minima between 200 and 250 m then increased to the bottom. Maxima do occur at the bottom of the mixed layer, but are probably remnants of summer surface warming rather than intrusions.

Bolus type parcels are observed in the intermediate water of Prince William Sound from spring through summer. These features are centered around temperature maxima which increase in magnitude throughout this season and appear deeper and deeper in the water column. Comparison of the size of individual boluses with the tidal prisim may give some indication of the manner of intrusion into the fjord. Little is known about the nature of the tides in the Sound, but they are assumed to be of the pure standing-wave type with very little change in vertical range or phase over the Sound (Mungall, 1973). Using this assumption, the tidal prism (Dyer, 1973) for Prince William Sound is found to be about 35 km^3 (surface area 8,835 km^2 x tidal range 0.004 km). The bolus contouring is approximate and only an order of magnitude size comparison is intended. The boluses are approximated as ellipsoids with dimensions taken from the temperature sections. Bolus size ranges from smaller to larger than a tidal prism. For example, in March 1972 (Fig. E) a 2.2°C parcel under the 2°C dome has a volume of 32 km^3 while a 2.4°C parcel in June 1972 (Fig. G) covers 135 km^3. As Ebbesmeyer (1973) pointed out, some mechanism in addition to tidal intrusions must contribute to exchange if the boluses were larger than the tidal prism. The importance of the wind as a driving force for exchange in Resurrection Bay has been discussed by Heggie and Burrell (1974) and could also be a factor in Prince William Sound.

It is proposed that these boluses represent advective intrusions of ocean water with subsequent exchange of intermediate fjord water. For this to be so, it is necessary to establish that the boluses do not result from processes within the fjord. The lack of concurrent fjord and ocean data during the summer of 1972 is a handicap. Data from GASS 1 are used (Sect. 4.1) to determine seasonal density differences and water mass cycles; however, the large spatial separation and temporal variation of the sampling does not allow the use of conservative water mass tracers (T-S and NO) to identify specific parcels. If warm, high salinity water presented on the Gulf shelf during the summer advects into the Sound it would interleaf with the fjord water seeking its own density level. Since the intermediate fjord water at this season is cold compared to both the warm surface and deep ocean water (Sect. 3.2), warm parcels intruding and retained at intermediate depths by their density would appear as temperature maxima prior to mixing. Such temperature maxima were observed as bolus cores during the summer of 1972. Coinciding with these temperature maxima are NO maxima which are not expected in the intermediate fjord water due to winter mixing and spring and summer production. It is expected that the warm, high salinity source water moving up onto the shelf during the summer would be higher in nutrients than the intermediate fjord water. The temperature and NO maxima seem to support intermediate advective intrusions as part of the exchange mechanism.

4.4. Deep Advective Exchange

Fractional exchange of deep water in Prince William Sound is predicted annually through advective inflows in late summer or autumn. To fully substantiate this exchange mechanism, current measurements in Hinchinbrook Entrance and Montague Strait along with concurrent hydrographic data from the fjord and ocean are necessary. In the absence of such data, the available hydrographic data is interpreted in terms of a simplified model (Sect. 3.1) of the physical system.

Seasonal cycling in the water mass characteristics of the ocean water outside Hinchinbrook Entrance (GASS 54) is similar to the cycling reported by Royer (1975) outside Resurrection Bay (GASS 1) (Sect. 4.1). Warm high salinity water appears outside the Entrance during summer, reaching a maximum by autumn. It is proposed (Sect. 4.1) that the deep, high salinity water of interest here moves up the 200 m channel to Hinchinbrook Entrance. Comparison of the source water with the fjord water (Sect. 4.2) shows that a density differences does develop during the summer reaching a maximum by early autumn. This is a necessary condition for deep advection.

If warm high salinity water appearing on the shelf during summer (Royer, 1975) advects into the deep basin, the deep fjord water should increase in both temperature and salinity. Salinity near the bottom of the deep basin increases from a minima in April or May of about 32.6 or 32.7 ‰ ($\sigma_t \cong 25.9$) to a maximum of over 32.9 ‰ ($\sigma_t \cong 26.1$) by September or October (Fig. 7). Temperature is also observed to increase during the summer (Fig. 7) from about 4°C to 5°C by autumn. This annual warming and salting of the deep water from 1971 to 1975 supports the idea that exchange is a consistently regular mechanism with a yearly period of occurrence. The variability of the temperature and salinity maxima from year to year indicates that the extent of the exchange is irregular.

Unusually warm (> 5°C), high salinity (> 33 ‰) appears in the deep basin on 9 September 1975 (Fig. 7). Upwelling indices (Bakun, 1973) for the previous week range from 10 to 30 m^3/second/100 m of coastline and do not exceed this range throughout the summer of 1975 or in previous summers. The absence of an unusually large upwelling index coinciding with this anomalous deep water suggests that the presence of high salinity source water outside the fjord is not the only factor influencing the exchange. A combination of bathymetry and wind induced deep inflow may restrict or enhance the exchange. For example, the open access to the Gulf, down channel winds and small basin of Resurrection Bay may be the reason why the deep water is consistently higher in salinity than in Prince William Sound.

Once ocean water advects into the Sound it can interleaf with the fjord water at the appropriate density level or move along the bottom uplifting the resident deep water. In either case, some form of turbulent mixing is expected over some time scale resulting in deep water which is a mixture of resident fjord water and ocean water. Conservative water mass tracers, such as temperature and salinity, are useful in determining the possibility of such mixing. T-S diagrams are useful for identifying water masses and their mixing. The lack of concurrent fjord and ocean data forces comparison using data from GASS 1. If deep advective exchange occurs in autumn, the resulting deep water (December, 1972) should be a mixture of resident deep water (September, 1972) plus ocean source water (October, 1972). The T-S characteristics of these water masses are compared (Fig. 16) and show that the winter fjord water lay between the resident fjord water and ocean water during 1972. This indicates that the expected mixing occurred. GASS 1 is not a true representation of the ocean source water so the comparison is only approximate. The lack of data throughout the summer of 1972 and for other years makes similar comparison difficult.

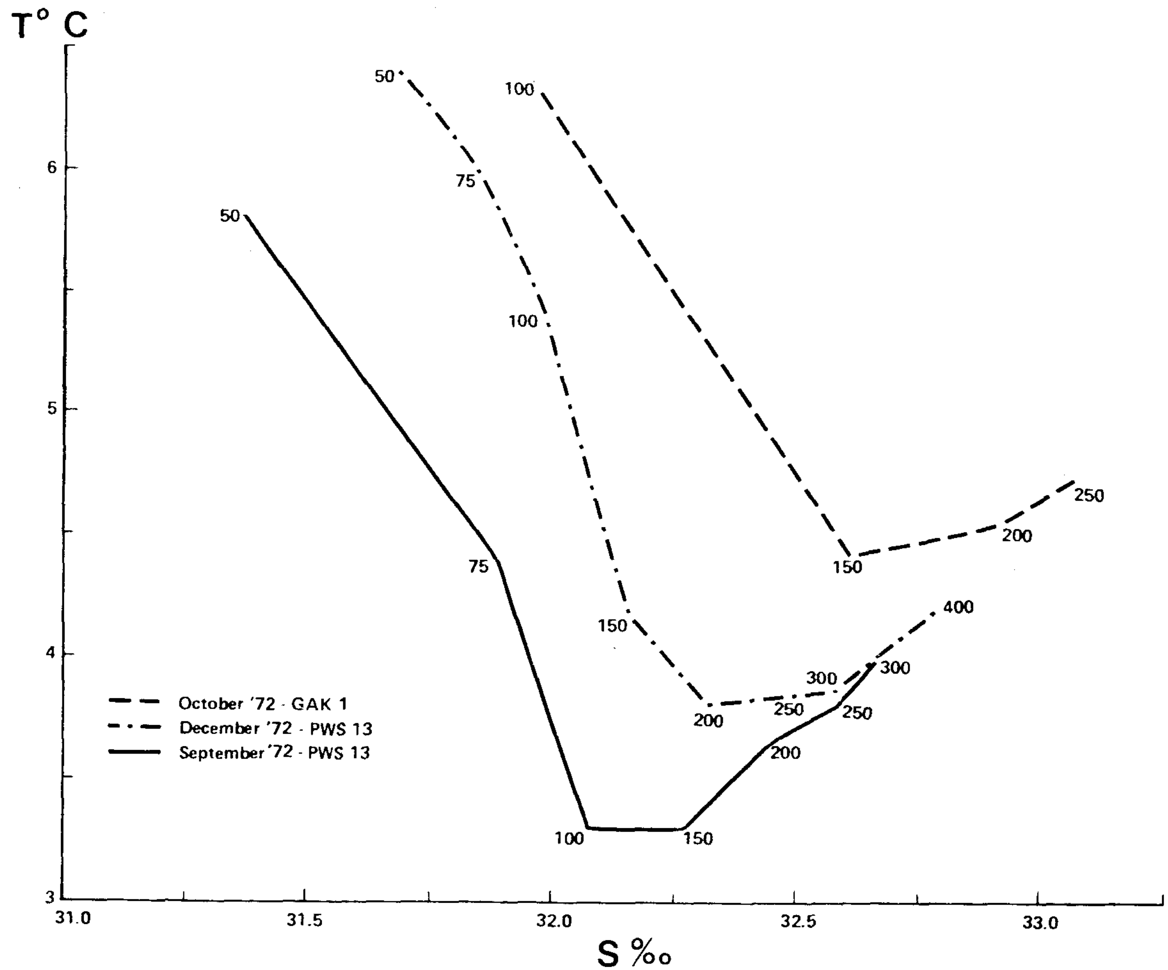

Figure 16. T-S diagrams for GAK 1 and PWS 13 during autumn of 1972.

The dissolved oxygen content of fjord basins can be a useful indicator of the frequency of deep exchange. Anoxic conditions in the bottom waters of some Canadian and Norwegian fjords have been observed, but it is not a common phenomenon in central Alaskan inlets. Generally, dissolved oxygen in Prince William Sound decreases with depth from a high value of over 7 ml/1 at the surface to 4.0-5.5 ml/1 at depth depending on the time of year (Fig. 8). If advective inflows to the deep basins are occuring during summer, the dissolved oxygen concentration should increase, reaching a maximum by autumn. With the cessation of deep advective inflows in autumn, the basin water would become isolated from oxygen rich water during the winter. This would result in some degree of oxygen depletion in the bottom water from ongoing respiration and bacterial decomposition. Significant oxygen depletion is observed by the end of winter (Fig. 8a, March 1972) but does not approach an anoxic situation. By autumn, oxygen increases from about 4.0 ml/1 to more than 5.0 ml/1 (Fig. 8c).

Linde (1970) and Gade (1973) presented a technique using elevation diagrams to quantify the extent of deep exchange. Gade (1973) pointed out: "by measuring the amount of lifting the overlying resident water masses are subjected to by bottom and deep water replacements, it is possible to determine the quantity of water that has entered the basin". This method assumes that the intrusion of deep source water does not mix with the surrounding or overlying layers. However, in Prince William Sound, the irregular bathymetry leading into the deep basin might cause some mixing. The technique is applied in hopes of gaining an estimate of the extent of exchange.

The summer of 1972 is the only season with adequate data covering the period of deep advective exchange. In June 1972 (Fig. G) the 26.0 σ_t surface lies at 400 m near the bottom of the deep basin while by September 1972 (Fig. H) it is at 300 m. This uplifting indicates that the volume between 300 and 400 m is added to the deep basin if all the water below the σ_t = 26.0 surface enters without mixing. This volume is about 50.2 km^3 if the basin is assumed elliptically cylindrical ($V = [A_{300} + A_{400}]/2 \times h$). This large sampling interval only brackets the period providing initial and final conditions. This does not provide an understanding of the duration of exchange that closely spaced hydrographic sampling and current measurements would. It is not possible to determine if the intrusions occur continuously on each flood tide or as intermittent events.

4.5 Deep Diffusive Exchange

The frequency of the proposed deep water exchange mechanism for Prince William Sound is directly related to the annual cycling in the water mass characteristics of the near bottom water on the Gulf of Alaska continental shelf (Sect. 3.3). This cycling results in an increasing density difference that allows deep advective exchange to reach a peak during late summer and early autumn. The density cycling of the source water is a necessary but not entirely sufficient condition for the advective exchange. If annual influxes are to occur, then there must be a mechanism to reduce the density of the basin water creating a density difference. This is a basic assumption of the proposed exchange mechanism. If such a mechanism did not exist, then the deep water would reach and maintain a maximum density inhibiting any further intrusions to the basin.

Vertical mixing through turbulent eddy diffusion is the mechanism proposed to account for the observed deep water salinity decrease during winter. Mixing of this type is observed in many fjords with Oslofjord, Norway (Gade, 1970) and Hebron Fjord, Labrador (Nutt and Coachman, 1956) being good examples. It is a complex process that is not well understood, but there are techniques available using the observed diffusion of some property to get some idea of the extent of mixing or nature of the turbulent field. These techniques are applied to the observed changes in salinity with the assumption that they represent the end result of a complex series of vertical and horizontal processes that cover the full range of time and length scales.

The gradual exchange of deep and intermediate fjord water through vertical mixing is discussed in terms of the coefficient of vertical eddy diffusion. This coefficient (K) is a measure of the rate of vertical exchange of a conservative property through the water and is expressed in terms of the flux (F) and vertical gradient of the property (P):

$$F(Z) = -K \frac{\partial P}{\partial Z}$$

This is a classical representation of the diffusive process which only gives an average picture of the many complex processes that result in the final distribution of the property of interest. Finally it is necessary to remember that K only gives the rate of vertical transfer of the specific property for which it is calculated, but may represent the extent of vertical mixing in the deep basin if the lateral gradients are small.

To determine coefficients of diffusion over the central deep basin of Prince William Sound, salinity data from PWS 13 for 6 December 1972, 28 January 1973 and 9 March 1973 are used. This is the only available winter data. Even though the temporal spacing is large for this type of calculation, it might give some order of magnitude estimate of the diffusion coefficient. Using a salt budget method from Nutt and Coachman (1956) diffusion coefficients are determined. The equation used is:

$$\int_{z}^{b} (S_2 - S_1)\, dZ = -\bar{K} \int_{t_1}^{t_2} \frac{\partial S}{\partial Z}\, dt$$

where S_2 and S_1 are the observed salinities at time t_2 and t_1, b is the depth at bottom, z is the depth of calculation and $\bar{K}$ is a mean value of K during the time from t_1 to t_2. $\frac{\partial S}{\partial Z}$ is determined from the vertical salinity profile. The calculated values of $\bar{K}$ (cm^2/sec) are:

Depth (m)	December 1972- January 1973	January 1973- March 1973
350	7.7	1.45
400	0.17	0.65

It is important to remember that major variations in the mixing regime could easily occur during this time. Even if these values only represent long term averages, they seem to indicate that the mixing decreases close to the bottom of the basin and is more intense during the early winter than late winter.

5. CONCLUSIONS

Some description of the exchange between Prince William Sound and the Gulf of Alaska is provided from the data. These observations are summarized here and some recommendations concerning future work are given.

5.1 Summary

Seasonal cycling in the water mass characteristics of the ocean source water outside Hinchinbrook Entrance (GASS 54) is similar to the cycling reported by Royer (1975) outside Resurrection Bay (GASS 1). Warm, high salinity deep water appears outside the Entrance during summer, reaching a seasonal maximum by early autumn. The salinity distribution indicates that ocean source water presented to Prince William Sound at Hinchinbrook Entrance is a combination of shelf water flowing westerly along the 100 m channel and water from the shelf break passing up the 200 m channel. Steeply sloping isopycnals observed in Hinchinbrook Entrance indicate that tidal currents may veer to the right of the channel during the peak of the flood and ebb tides. There may also be a two way flow during the change of the tide (Sect. 4.2).

The exchange of the intermediate water in the Sound is a regular annual phenomenon occuring throughout the summer. It is proposed that bolus type parcels of water observed at intermediate depths represent advective intrusions of ocean water with subsequent exchange of intermediate fjord water. These boluses are centered around temperature and NO maxima which increase in magnitude and appear deeper and deeper in the water column throughout the summer (Sect. 4.3). Boluses are observed that are larger than a tidal prism, indicating that some mechanism in addition to tidal intrusions may contribute to the exchange.

Deep advective exchange is also observed to be an annual event. The warming and salting of the deep water to an early autumn maxima from 1971 to 1975 indicates that the exchange is a regular phenomenon with a yearly period of occurrence. The yearly variability of the temperature and salinity maxima indicate that the extent of exchange is irregular. Indirect measurement of the exchange (Sect. 4.4) during the summer of 1972 indicate an intrusion of about 60 km^3. From the available data it is not possible to determine if the intrusions occur continuously or as intermittent events of variable duration and extent. Early in the summer, fractional exchange probably occurs, while by autumn the density differences and intermittent wind driven transport may be large enough to completely exchange the deep water.

Deep diffusive exchange probably occurs throughout the year being more evident during the winter in the absence of advective intrusions. The deep water continues to increase in temperature while the salinity decreases as a result of this vertical mixing. Diffusion coefficients (Sect. 4.5) indicate that mixing at 350 m is stronger than at 400 m. The large sampling interval probably averages out most details of the mixing process.

5.2 Recommendations for Future Study

The available data for Prince William Sound are useful to describe the seasonal variations in the hydrographic structure and to propose a circulation regime. It is proposed that a longshore westerly flow and deep onshore flow converge at Hinchinbrook Entrance. This water would move into the Sound under the influence of tidal currents and possibly the counterclockwise gyre suggested by the doming isopleths. Continuity would require outflow through Montague Strait. Included in this circulation regime are the deep and intermediate exchanges already discussed. Finally it is expected that the wind is an important factor in influencing the circulation.

To varify this proposed circulation regime the following program of measurements is suggested. Basically it consists of current and meteorological measurements supported by hydrographic measurements. The suggested locations for current meter arrays and meteorological buoys are:

1. Current meter arrays located at both PWS 42 and 43 in Hinchinbrook Entrance.

2. Current meter array located at PWS 37 in Montague Strait.

3. Current meter arrays and meteorological buoys at PWS 44, 45 and 55 in central Prince William Sound.

Tide gauges should also be included in the sampling program either in conjunction with the current meter arrays or at shore stations. Hydrographic data should be taken in the adjacent coastal areas as well as in the fjord. Nutrient and oxygen measurements should be included in the hydrographic work.

This type of sampling should provide information on a number of questions connected with the circulation in Prince William Sound. First, it would quantitatively document any circulation patterns through Hinchinbrook Entrance, around the Sound and out Montague Strait. The current meters and their synoptic temperature and salinity measurements would also determine the duration and extent of deep and intermediate intrusions. This information is not available from the existing data. It would also be possible to measure the influence of the wind and passing storms on the circulation. The hydrographic data would provide concurrent measurements of conservative properties (T, S, and NO) useful as tracers and in water mass analysis. Finally, tide measurements not presently available could be made covering the central Sound.

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APPENDICES

APPENDIX A

STATION LOCATIONS

Prince William Sound Stations

Location	Number	Latitude °N	Longitude °W
VAA	1	60 50.0	147 01.0
PFI	2	60 46.0	146 45.5
PFI	3	60 47.8	146 26.0
PFI	4	60 51.3	146 13.0
PGR	5	60 37.4	146 36.0
	6	60 32.5	146 36.0
PGR	7	60 41.7	146 13.0
PGR	8	60 37.4	146 24.8
ORB	9	60 33.3	146 12.8
ORB	10	60 35.4	145 58.7
HIE	11	60 19.0	146 49.0
	12	60 27.0	146 54.0
	13	60 35.0	146 55.0
	14	60 27.0	147 11.0
	15	60 36.0	147 14.0
	16	60 42.0	147 00.0
	17	60 47.0	147 13.8
COL	18	60 56.0	147 06.0
UNI	19	60 53.0	147 32.0
UNI	20	60 58.0	147 34.0

Location	Number	Latitude °N	Longitude °W
UNI	21	61 03.2	147 33.4
	22	60 46.5	147 32.5
	23	60 43.2	147 47.0
COF	24	61 10.5	147 49.5
PWE	25	60 55.8	148 11.2
PWE	26	60 47.5	148 24.0
WEP	27	60 46.3	148 07.5
	28	60 40.5	147 41.0
PWE	29	60 42.8	148 12.0
PNJ	30	60 34.2	148 12.9
PNJ	31	60 32.2	148 32.1
	32	60 31.1	147 47.2
	33	60 33.4	147 30.6
KIP	34	60 18.0	147 59.0
	35	60 16.3	147 36.0
KIP	36	60 05.6	147 48.8
MOS	37	59 58.8	147 50.5
	38	60 16.2	147 38.6
	39	60 15.5	147 33.0
	40	60 26.8	147 02.8
	41	60 28.0	146 45.4
HIE	42	60 18.5	146 51.9

Location	Number	Latitude °N	Longitude °W
HIE	43	60 19.7	146 45.7
	44	60 33.7	146 45.6
	45	60 35.6	147 04.8
	46	60 41.8	147 10.0
	47	60 43.0	146 50.0
	48	60 49.6	147 11.0
	49	60 45.2	147 16.2
	50	60 46.0	147 26.2
	51	60 49.2	147 26.5
PGR	52	60 34.5	147 24.0
ORB	53	60 35.3	146 12.8
	54	60 38.8	146 52.8
	55	60 46.1	147 01.6
	56	60 46.0	147 38.6
	57	60 44.4	147 33.3
	58	60 39.9	147 35.5
PWE	59	60 54.6	148 08.5
	60	61 04.4	147 58.0
PEP	61	60 40.2	148 02.0
	62	60 31.5	147 51.8
KIP	63	60 07.8	147 47.0
MOS	64	59 57.1	147 47.6

Location	Number	Latitude °N	Longitude °W
VAA	101	60 55.1	146 52.8
VAA	107	61 00.3	146 45.9
PVN	114	61 04.1	146 39.7
PVA	139	61 06.4	146 23.1

LOCATION NAMES

COF	College Fjord
COL	Columbia Bay
HIE	Hinchinbrook Entrance
KIP	Knight Island Passage
MOS	Montague Strait
ORB	Ocra Bay
PEP	Perry Passage
PNJ	Port Nellie Juan
PFI	Port Fidalgo
PGR	Port Gravina
PWE	Port Wells
UNI	Unakwik Inlet
VAA	Valdez Arm
WEP	Wells Passage

No location name indicates stations are in the central portion of Prince William Sound.

Early Prince William Sound Stations

Location	Number	Latitude °N	Longitude °W
PWS	1	60 30.0	147 10.9
PWS	2	60 34.8	146 55.0
PWS	5	60 50.0	147 00.8
PWS	6	60 48.5	147 16.2
PWS	155	60 44.6	147 02.7
PWS	156	60 40.0	146 45.0

Gulf of Alaska Stations

Location	Number	Latitude °N	Longitude °W
GASS	1	59 50.2	149 30.5
GASS	2	59 41.5	149 22.0
GASS	3	59 33.0	149 13.2
GASS	4	59 24.5	149 04.9
GASS	5	59 16.0	148 56.0
GASS	6	59 07.2	148 47.5
GASS	7	58 58.7	148 38.7
GASS	8	58 49.7	148 30.0
GASS	9	58 41.1	148 21.6
GASS	10	58 32.3	148 13.2
GASS	11	58 23.2	148 04.8
GASS	12	58 22.1	147 18.8
GASS	13	58 20.7	146 32.5
GASS	14	58 19.6	145 46.5
GASS	15	58 18.1	145 00.5
GASS	16	58 16.9	144 14.8
GASS	17	58 15.4	143 28.5
GASS	18	58 14.1	142 42.1
GASS	19	58 13.0	141 55.0
GASS	20	58 21.2	141 44.0

Location	Number	Latitude °N	Longitude °W
GASS	21	58 29.5	141 33.0
GASS	22	58 38.0	141 22.2
GASS	23	58 46.1	141 11.3
GASS	24	58 54.3	141 00.5
GASS	25	59 02.5	140 49.8
GASS	26	59 10.8	140 38.9
GASS	27	59 18.6	140 27.9
GASS	28	59 26.5	140 16.9
GASS	29	59 34.6	140 06.0
GASS	30	59 44.1	141 27.9
GASS	31	59 35.2	141 36.8
GASS	32	59 26.3	141 46.0
GASS	33	59 17.5	141 54.8
GASS	34	59 08.5	142 03.8
GASS	35	58 59.5	142 13.0
GASS	36	59 06.5	143 04.0
GASS	37	59 16.2	142 59.2
GASS	38	59 25.9	142 54.2
GASS	39	59 35.7	142 49.5
GASS	40	59 45.5	142 44.5
GASS	41	59 55.1	142 39.5
GASS	42	59 55.1	143 51.2

Location	Number	Latitude °N	Longitude °W
GASS	43	59 45.0	143 52.8
GASS	44	59 35.0	143 54.2
GASS	45	59 24.9	143 55.8
GASS	46	59 14.6	143 56.9
GASS	47	59 17.5	145 13.0
GASS	48	59 27.5	145 11.5
GASS	49	59 37.5	145 10.0
GASS	50	59 47.7	145 09.0
GASS	51	59 57.6	145 07.8
GASS	52	60 07.6	145 06.5
GASS	53	60 23.0	146 54.0
GASS	54	60 13.9	146 48.6
GASS	55	60 04.5	146 42.6
GASS	56	59 55.2	146 36.8
GASS	57	59 45.6	146 31.0
GASS	58	59 36.2	146 25.5
GASS	59A	59 17.1	146 14.0
GASS	59B	59 07.6	145 53.4
GASS	60	60 01.5	145 51.2
GASS	61	59 34.2	145 46.9
GASS	62	59 33.2	142 16.0
GASS	63	59 49.5	142 03.8

Location	Number	Latitude °N	Longitude °W
GASS	64	59 35.9	143 34.8
GASS	65	59 07.8	140 43.0
GASS	66	59 24.5	146 43.0
GASS	67	59 39.5	144 31.8

APENDIX B

CRUISE SUMMARY

Prince William Sound Cruises

Cruise Date No.	March 1972 129	June 1972 137	Sept. 1972 141	Dec. 1972 147	Jan. 1973 153	March 1973 159	May 1973 164	Oct. 1973 181	May 1974 188	March 1975 207
Station										
1	S	S	N	O	O	S	S		S	S
2	S	S	S	S			S			
3	N						S			
4	S									
5	S	S	S	S			S			
6	S	S	S	S			S		S	
7	S								S	
8	S			S						
9	S			S						
10	N								S	
11	N	S	N	O		O	O			S
12	S	S	N	O	O	O	O	S		
13	N	S	N	O	O	O	O		S	N
14	S	S	S	S		S	S			
15		S		S		S	S			
16	N	S	N	O	O	O	O			S
17	N	S	N	O	O		O			
18	S						S			
19	S									
20	S									

	March 1972 129	June 1972 137	Sept. 1972 141	Dec. 1972 147	Jan. 1973 153	March 1973 159	May 1973 164	Oct. 1973 181	May 1974 188	March 1975 207
21	S									
22	N									S
23	S									
24	S									
25	S									
26	S									
27	N									
28	N			S			S			S
29	S									
30	S									
31	S									
32										
33	S		N	S	S		S			
34	S									
35	N		N	O	S	O	O	S		
36	N		S							
37	N		N	O		O	O	S	S	
38	S		S	S	S	S	S			
39	S		S	S	S	S	S			
40	S		S	S		S	S			

	March 1972 129	June 1972 137	Sept. 1972 141	Dec. 1972 147	Jan. 1973 153	March 1973 159	May 1973 164	Oct. 1973 181	May 1974 188	March 1975 207
41	S	S	S			S	S			
42	S	S	S	S		S	S		S	
43	S	S	S	S		S	S		S	
44			S	S		S	S		S	
45	S		S	S		S	S			
46	S		S	S	S	S	S			
47			S	S		S	S		S	
48		S	S		S		O			
49	S	S	S	S	S		S			
50	S						S			
51	S			S			S			
52	N			S			S		S	
53	S			S					S	
54	N	S	S	S			S			
55	N	S	S	S			S		S	S
56	S			S						
57	S									
58	S			S						
59	N									
60										

	March 1972 129	June 1972 137	Sept. 1972 141	Dec. 1972 147	Jan. 1973 153	March 1973 159	May 1973 164	Oct. 1973 181	May 1974 188	March 1975 207
61	N									
62	N									
63	S		S							
64	S		S	S		S	S	S		
101			S	S	S	S	S			
107		S	S	S	O	O	O			
113		S	S							
114				S	S	S	S			
139		S		O	O	O	O			
172		S								

<u>Number of stations occupied</u>

Total	58	22	33	39	16	24	39	4	14	6
Nutrients	17	0	9	0	0	0	0	0	0	1

S - STD cast with Nansen bottle calibration

O - STD and Nansen cast with dissolved oxygen measurements

N - STD and Nansen cast with dissolved oxygen and nutrient measurements

Early Prince William Sound Cruises

Cruise Date No.	May 1971 113	July 1971 117	Oct. 1971 123	Dec. 1971 125	April 1972 131
Station					
PWS 1	S	O	S	S	
PWS 2	O	O	O	S	N
PWS 5	N	O	N	N	N
PWS 6	O	O	N		S
PWS 155	O	O	S		S
PWS 156	O	S	S	S	S
KIP 6			O		
PWS 1 (new)					S

Number of stations occupied

Total	6	6	7	4	6
Nutrients	1	0	2	1	2

S - STD cast with Nansen bottle calibration
O - STD and Nansen cast with dissolved oxygen measurements
N - STD and Nansen cast with dissolved oxygen and nutrient measurements

APPENDIX C

CLIMATOLOGICAL SUMMARIES

TABLE 1

Climatological Data for Cape Hinchinbrook[a]

Month	(26) Temp °C	(26) Precip. (cm)	(20) Snow and Sleet (cm)	Wind Speed (m/sec)	Wind Direction
Jan.	-0.61	17.043	47.498		
Feb.	0.22	16.713	50.292	(data not available)	
March	0.50	14.961	45.466		
April	3.22	13.767	17.526		
May	6.61	16.180	1.778		
June	10.33	11.913	0.0		
July	12.50	18.694	0.0		
August	12.78	23.444	0.0		
Sept.	10.22	32.715	0.0		
Oct.	5.78	31.191	10.160		
Nov.	2.39	20.726	24.130		
Dec.	0.00	22.250	43.688		
Annual	5.33	239.598	240.538		

(   ) Length of record, years (through 1970)

TABLE 2

Climatological Data for Cardova Airport[a]

Month	(29) Temp °C	(29) Precip. (cm)	(20) Snow and Sleet (cm)	(14) Wind Speed (m/sec)	(19) Wind Direction
Jan.	-4.94	15.494	63.500	2.06	E
Feb.	-3.22	11.786	57.150	2.15	E
March	-1.61	9.754	62.230	2.20	E
April	2.33	10.973	28.448	2.41	ESE
May	6.50	12.852	3.556	2.37	ESE
June	10.11	8.839	0.0	2.10	SW
July	11.78	15.926	0.0	1.83	E
August	11.33	20.472	0.0	1.70	E
Sept.	8.67	31.775	Trace	2.28	E
Oct.	4.33	30.226	6.604	2.50	E
Nov.	-0.50	20.371	26.162	2.37	E
Dec.	-3.56	17.221	69.088	2.28	E
Annual	3.44	205.689	316.738	2.19	E

( ) Length of record, years

TABLE 3

Climatological Data for Latouche[a]

Month	(20) Temp °C	(20) Precip. (cm)	(16) Snow and Sleet (cm)	Wind Speed (m/sec)	Wind Direction
Jan.	-0.83	41.224	76.200		
Feb.	0.06	39.827	61.468	(data not available)	
March	0.72	41.580	84.328		
April	2.78	38.024	28.702		
May	6.39	30.683	2.286		
June	10.33	15.951	0.0		
July	12.83	17.780	0.0		
August	13.00	31.471	0.0		
Sept.	10.11	44.298	Trace		
Oct.	5.89	61.011	3.556		
Nov.	2.06	48.412	24.384		
Dec.	-0.17	49.378	70.866		
Annual	5.28	459.638	351.790		

( ) Length of record, years

TABLE 4

Climatological Data for Valdez[a]

Month	(29) Temp °C	(29) Precip. (cm)	(48) Snow and Sleet (cm)	Wind Speed (m/sec)	Wind Direction
Jan.	-7.67	14.707	143.002		ENE
Feb.	-5.67	12.395	119.888	(data not	ENE
March	-3.22	9.398	93.218	available)	ENE
April	1.61	7.518	33.274		SW
May	6.17	8.839	5.334		SW
June	13.56	6.629	0.0		SW
July	11.50	11.989	Trace		SW
August	10.89	16.459	0.0		SW
Sept.	7.78	21.285	0.025		SW
Oct.	2.89	20.193	21.336		E
Nov.	-3.22	15.926	78.740		ENE
Dec.	-6.83	13.081	125.984		NE
Annual	2.06	158.420	621.030		SW

( ) Length of record, years

TABLE 5

Climatological Data for Whittier[a]

Month	(20) Temp °C	(20) Precip. (cm)	(14) Snow and Sleet (cm)	Wind Speed (m/sec)	Wind Direction
Jan.	-3.61	37.262	145.288		SW
Feb.	-2.83	27.153	129.032	(data not	SW
March	-2.39	26.670	94.996	available)	SW
April	2.22	27.889	63.246		NE
May	6.56	39.421	3.048		NE
June	11.06	25.730	0.0		SW
July	13.33	31.013	0.0		NE
August	12.72	36.551	Trace		NE
Sept.	9.06	46.025	Trace		NE
Oct.	3.50	52.883	18.034		SW
Nov.	-1.39	42.875	48.768		SW
Dec.	-3.67	51.740	167.640		SW
Annual	3.72	445.211	670.052		SW

( ) Length of record, years

[a]Tabulated from: U.S. Department of Commerce, NOAA-Environmental Data Service, Climatological Data Summary.

APPENDIX D

LONGITUDINAL SECTIONS

NA - data not available
( ) - temperature minimum
< > - temperature maximum

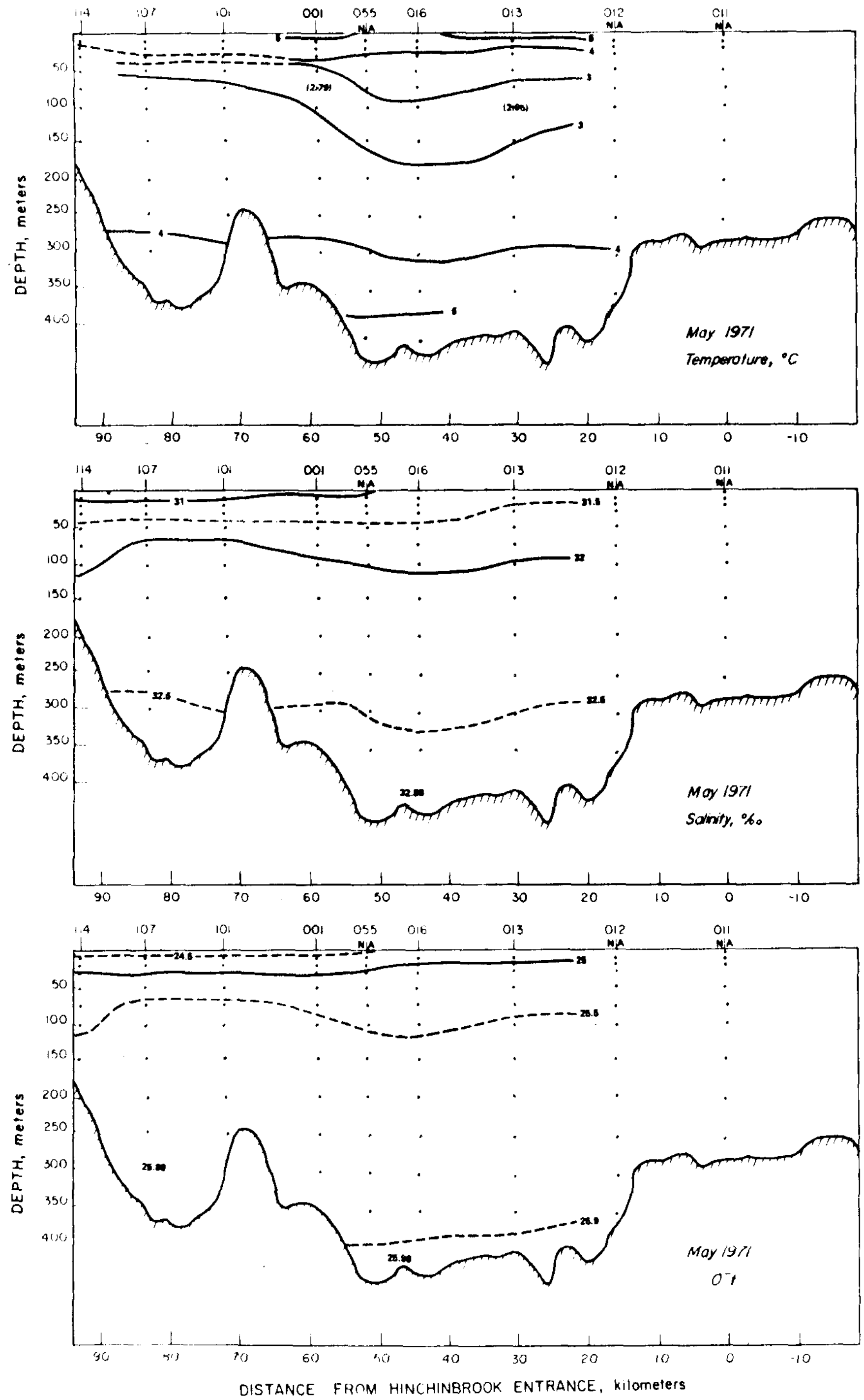


Figure A. Longitudinal hydrographic sections for May 1971.

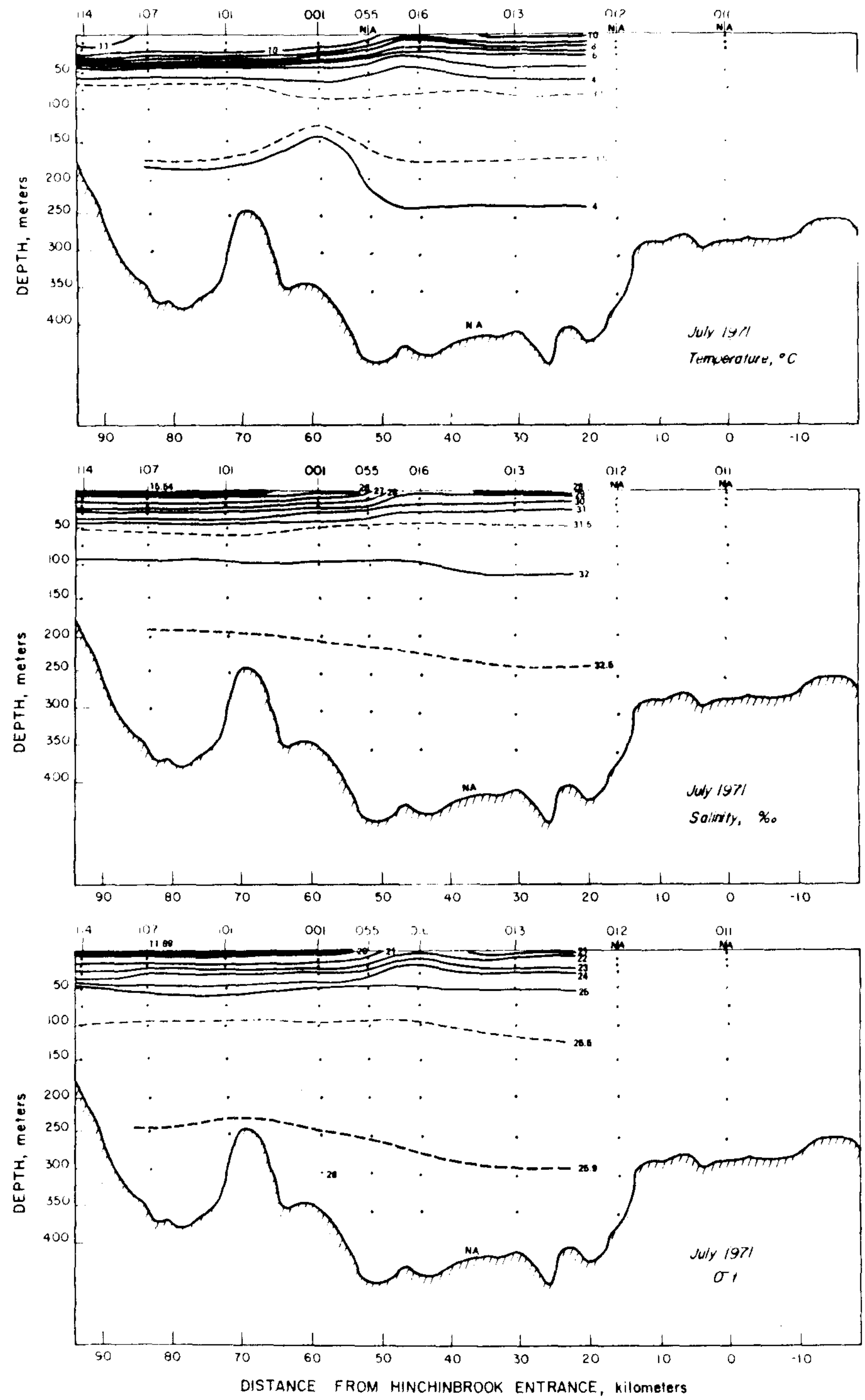


Figure B. Longitudinal hydrographic sections for July 1971.

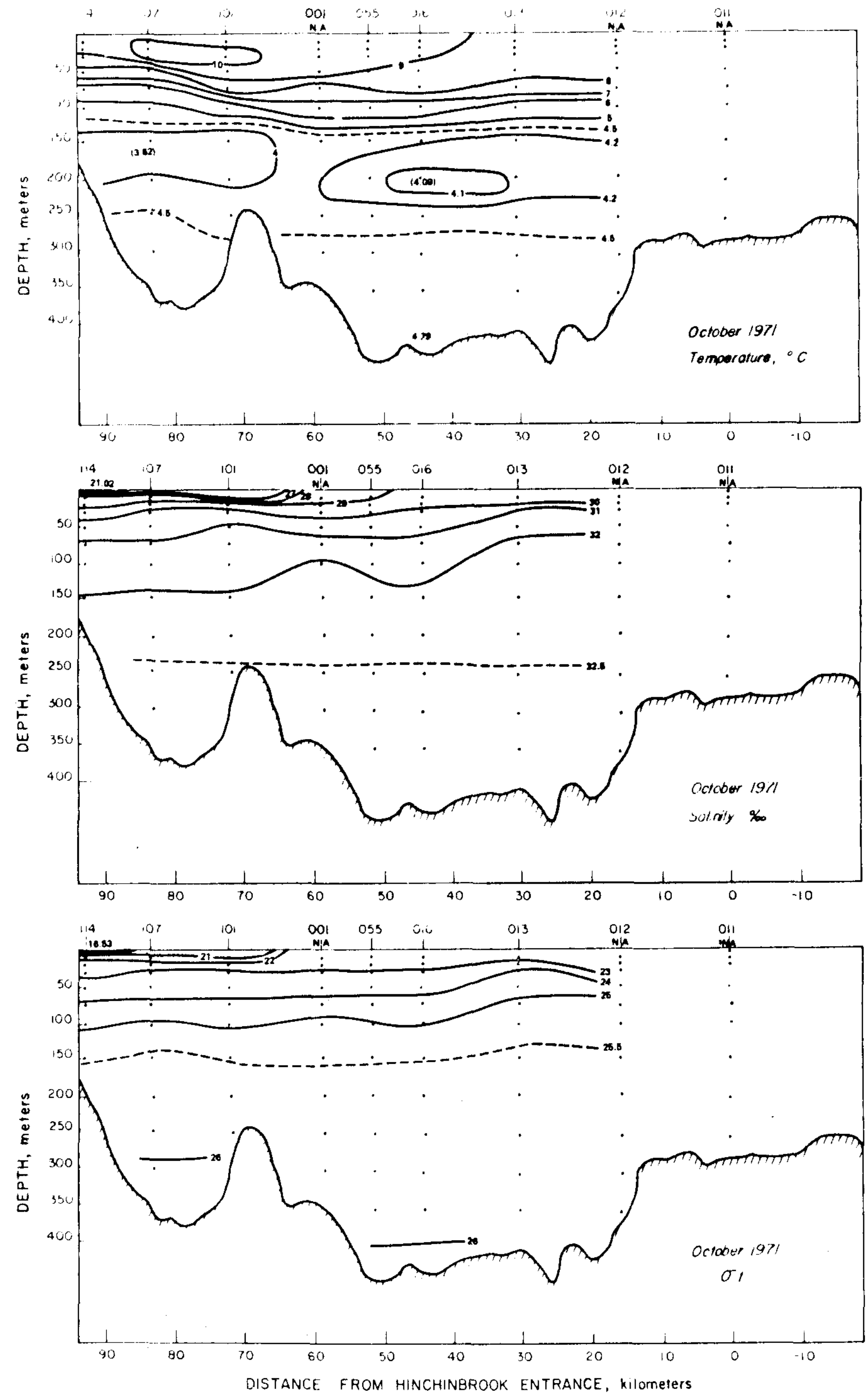


Figure C. Longitudinal hydrographic sections for October 1971.

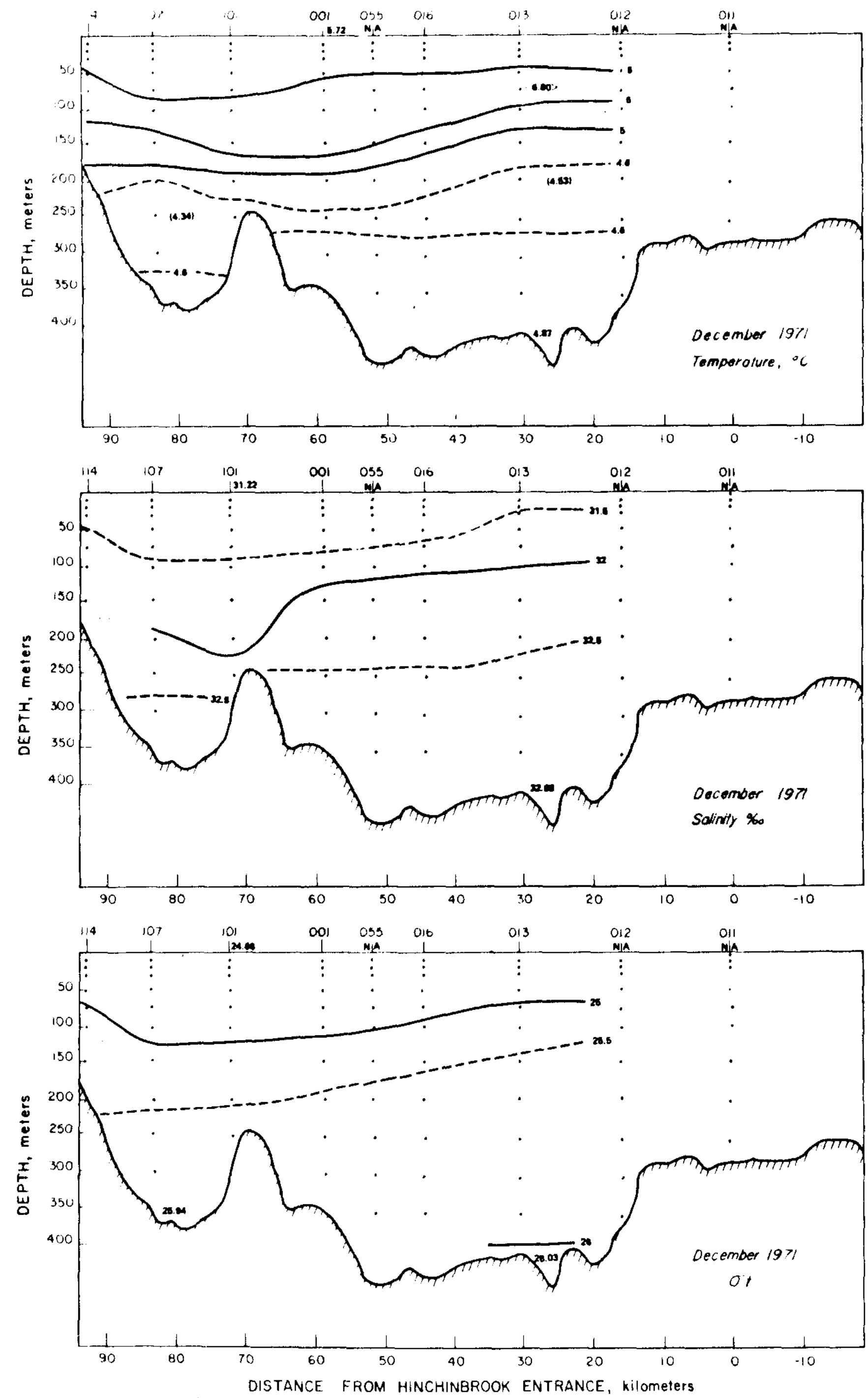


Figure D. Longitudinal hydrographic sections for December 1971.

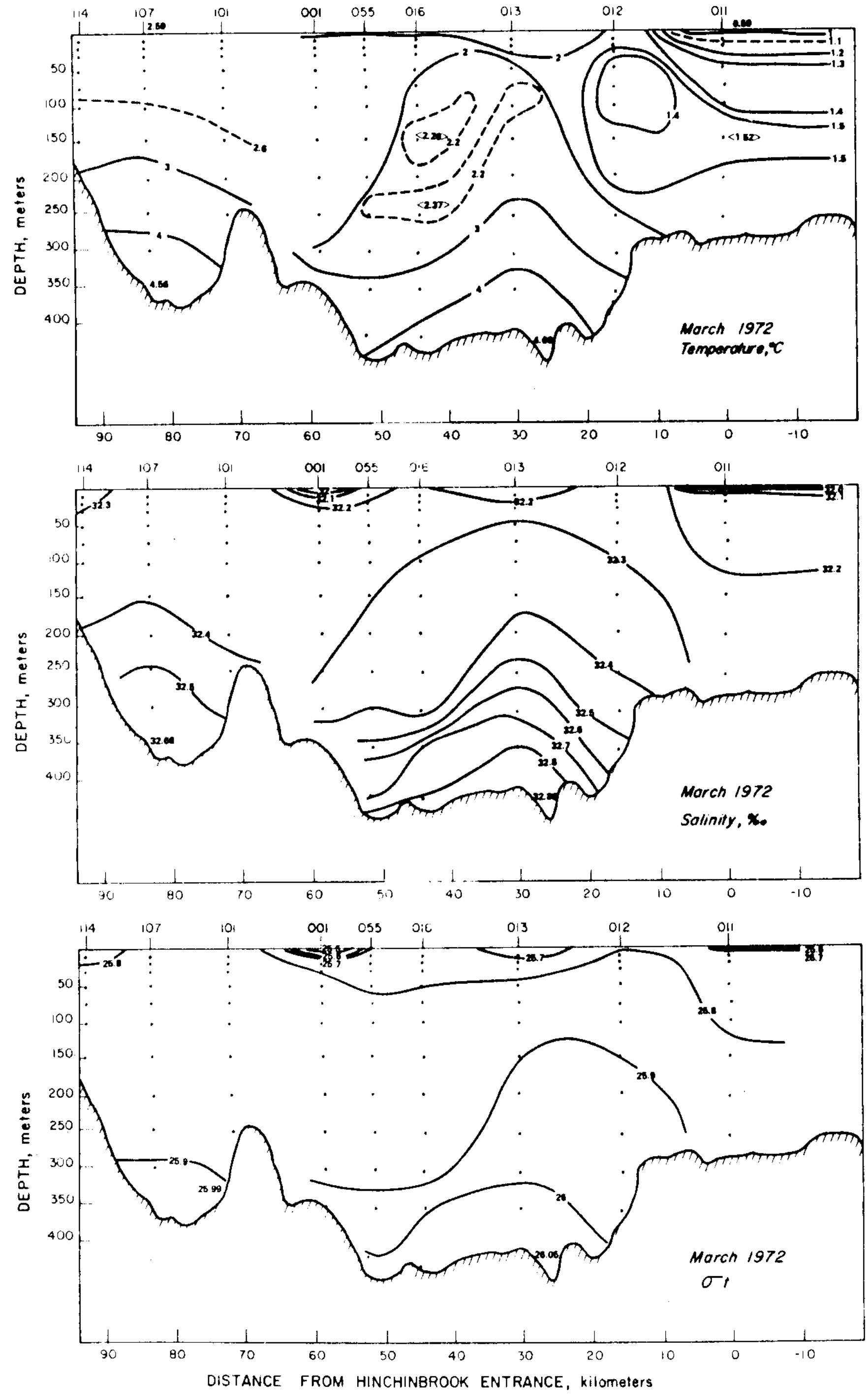


Figure E. Longitudinal hydrographic sections for March 1972.

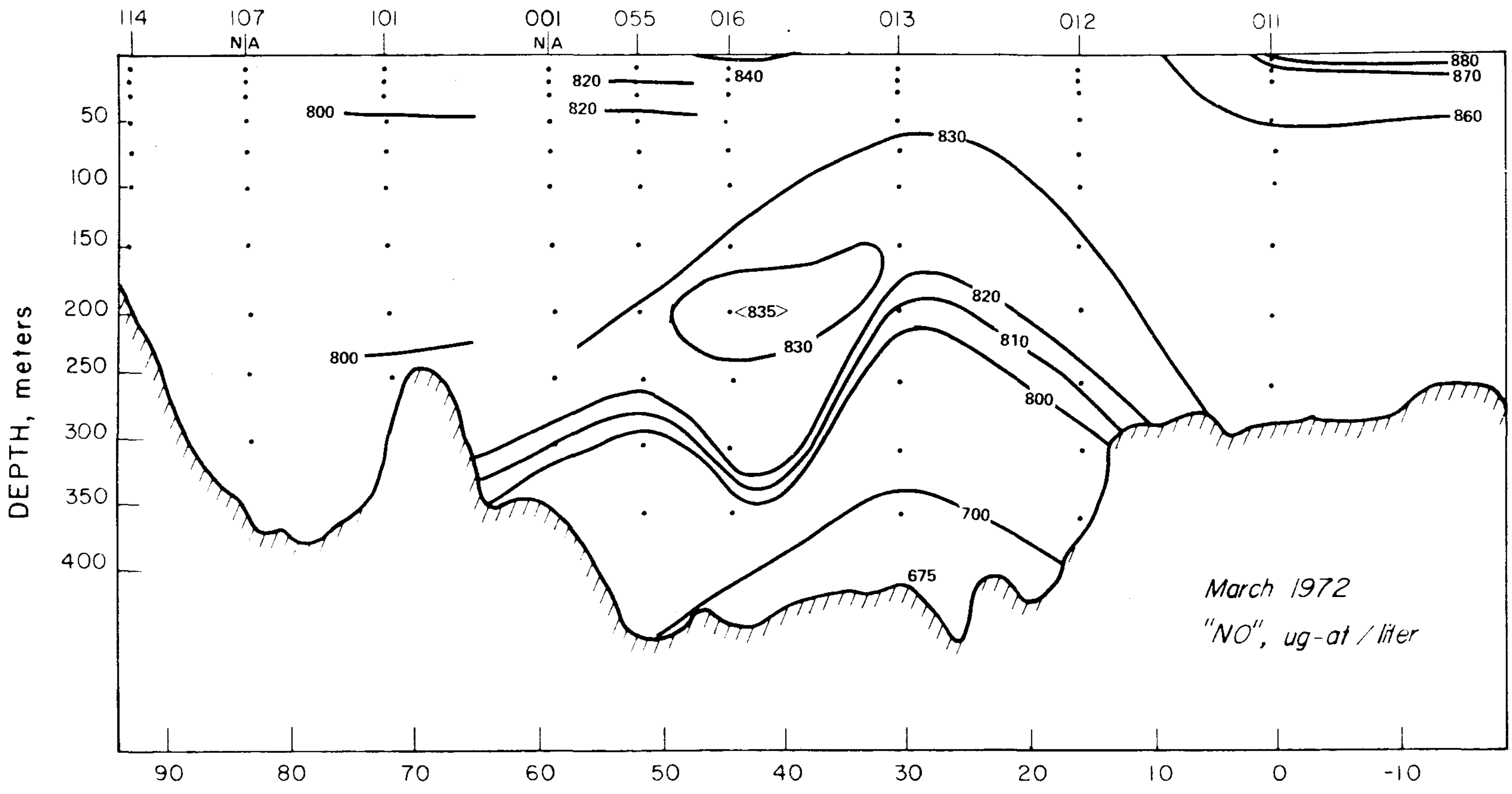


Figure NE. Longitudinal "NO" section for March 1972.

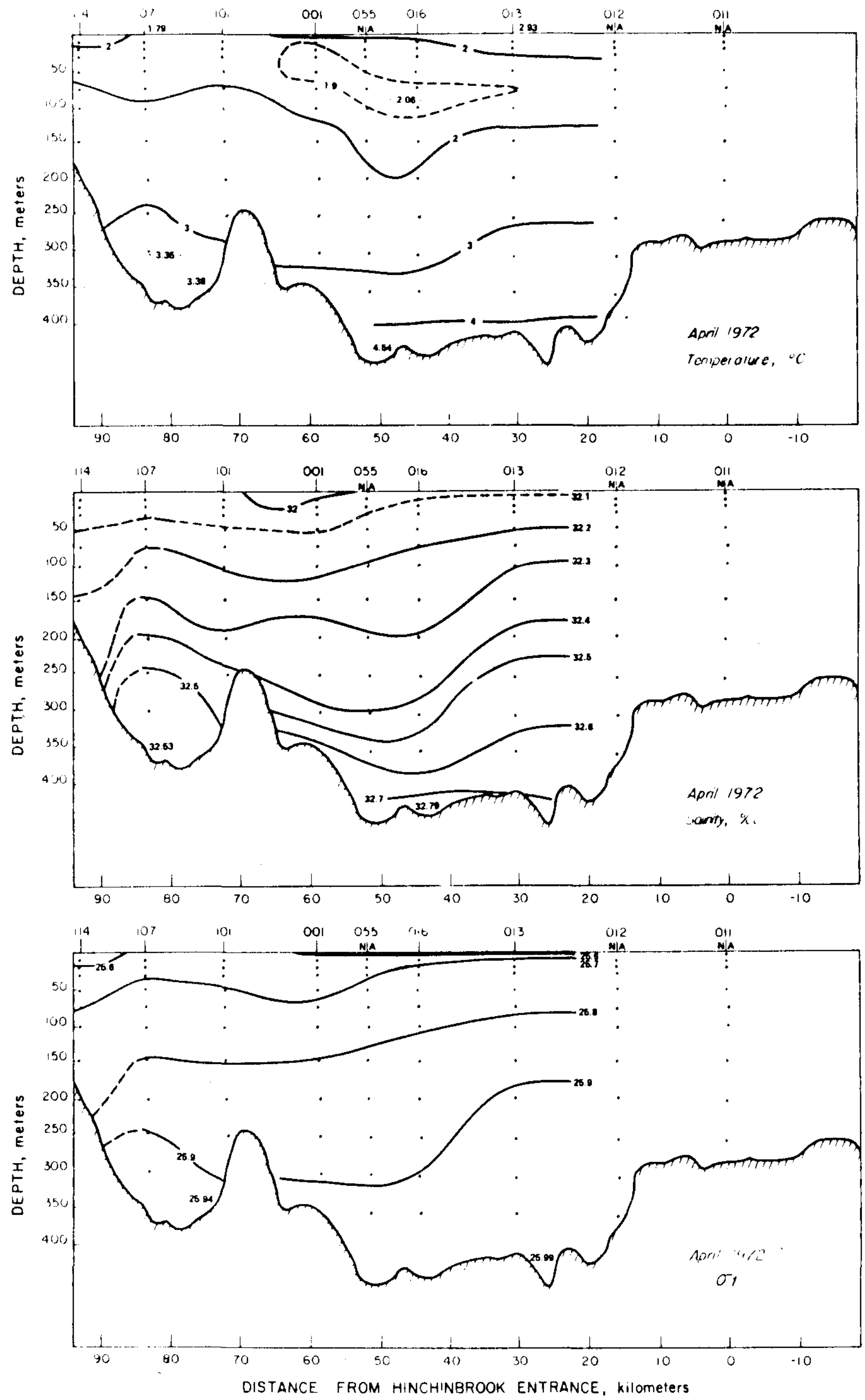


Figure F. Longitudinal hydrographic sections for April 1972.

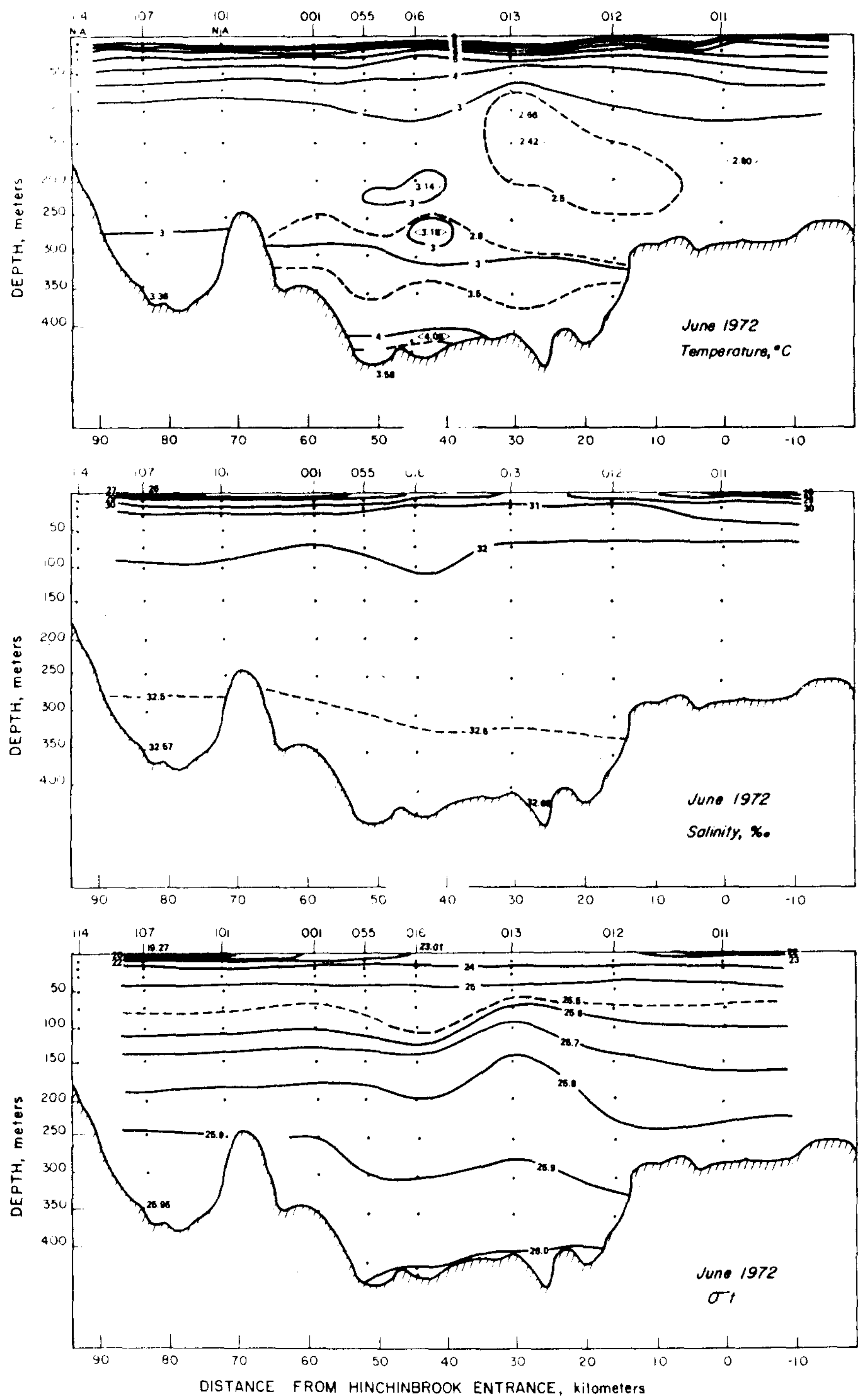


Figure C. Longitudinal hydrographic sections for June 1972.

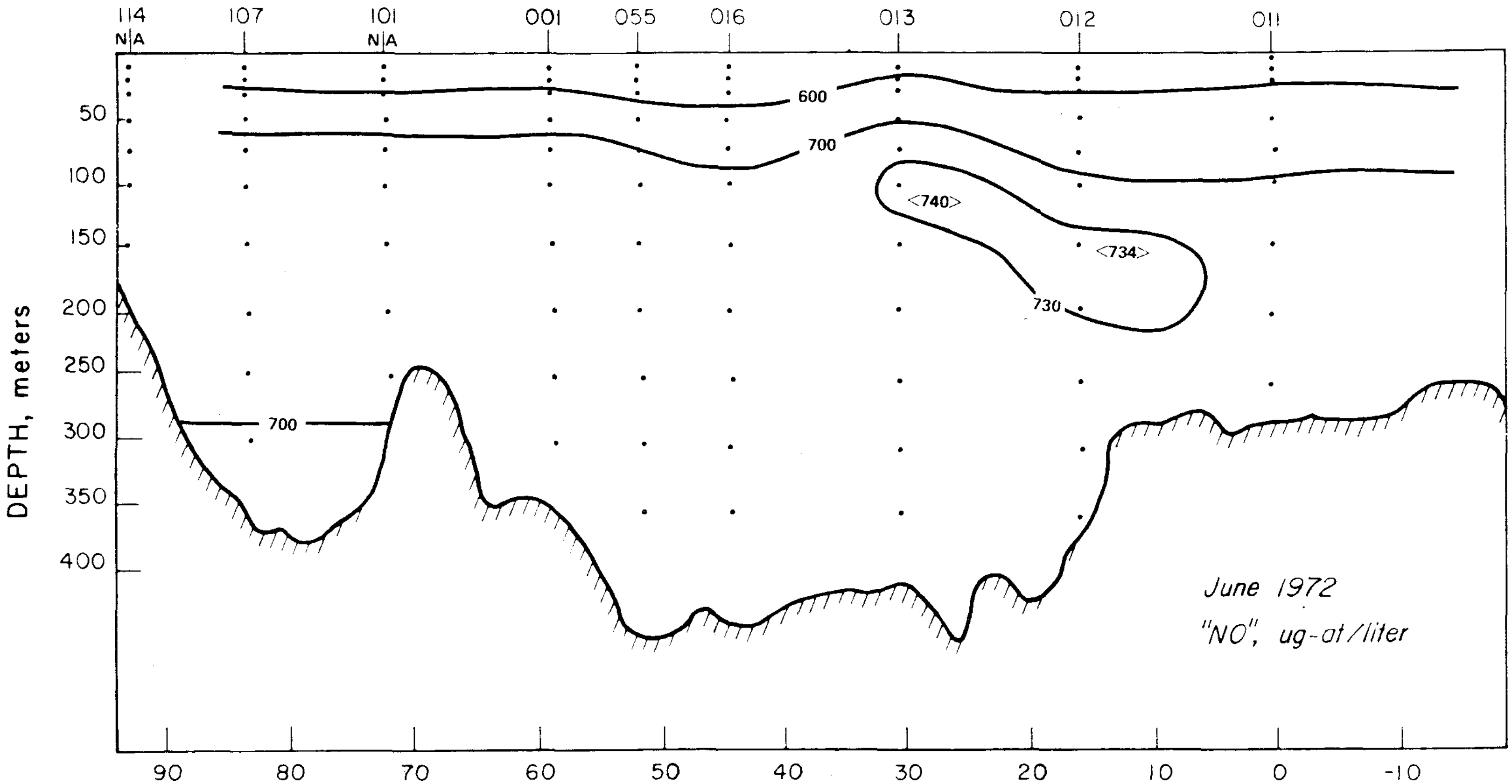


Figure NG. Longitudinal "NO" section for June 1972.

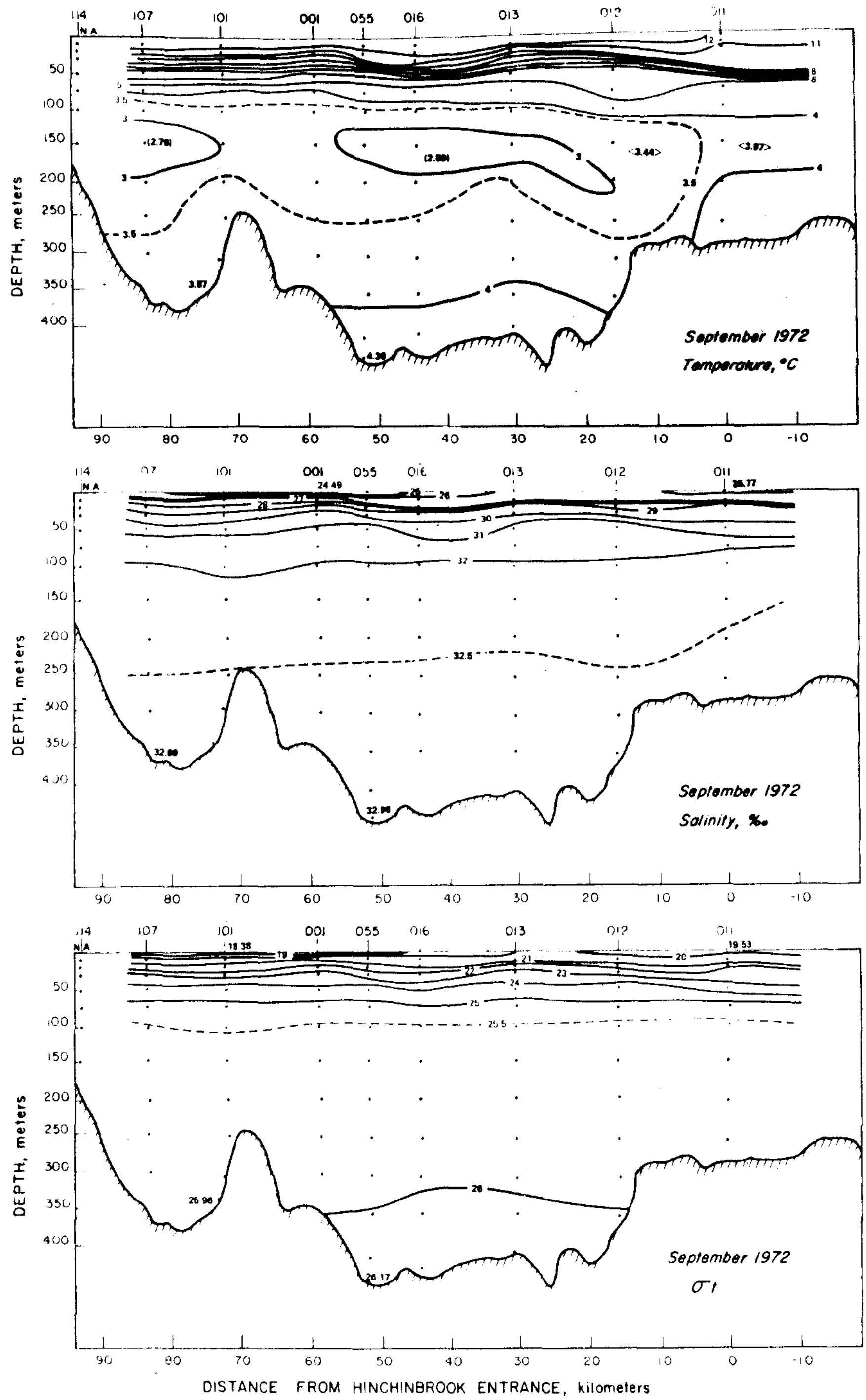


Figure H. Longitudinal hydrographic sections for September 1972.

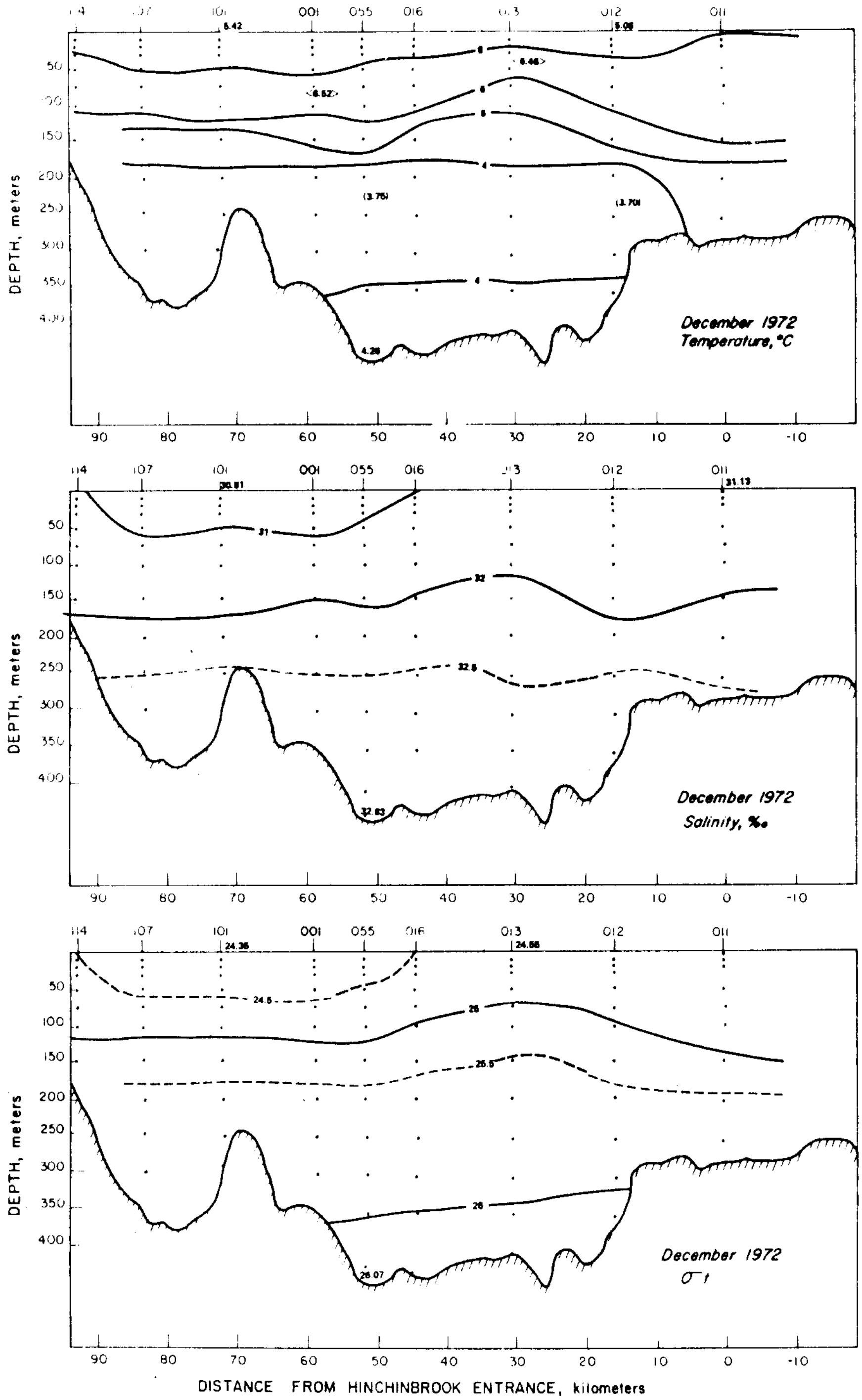


Figure I. Longitudinal hydrographic sections for December 1972.

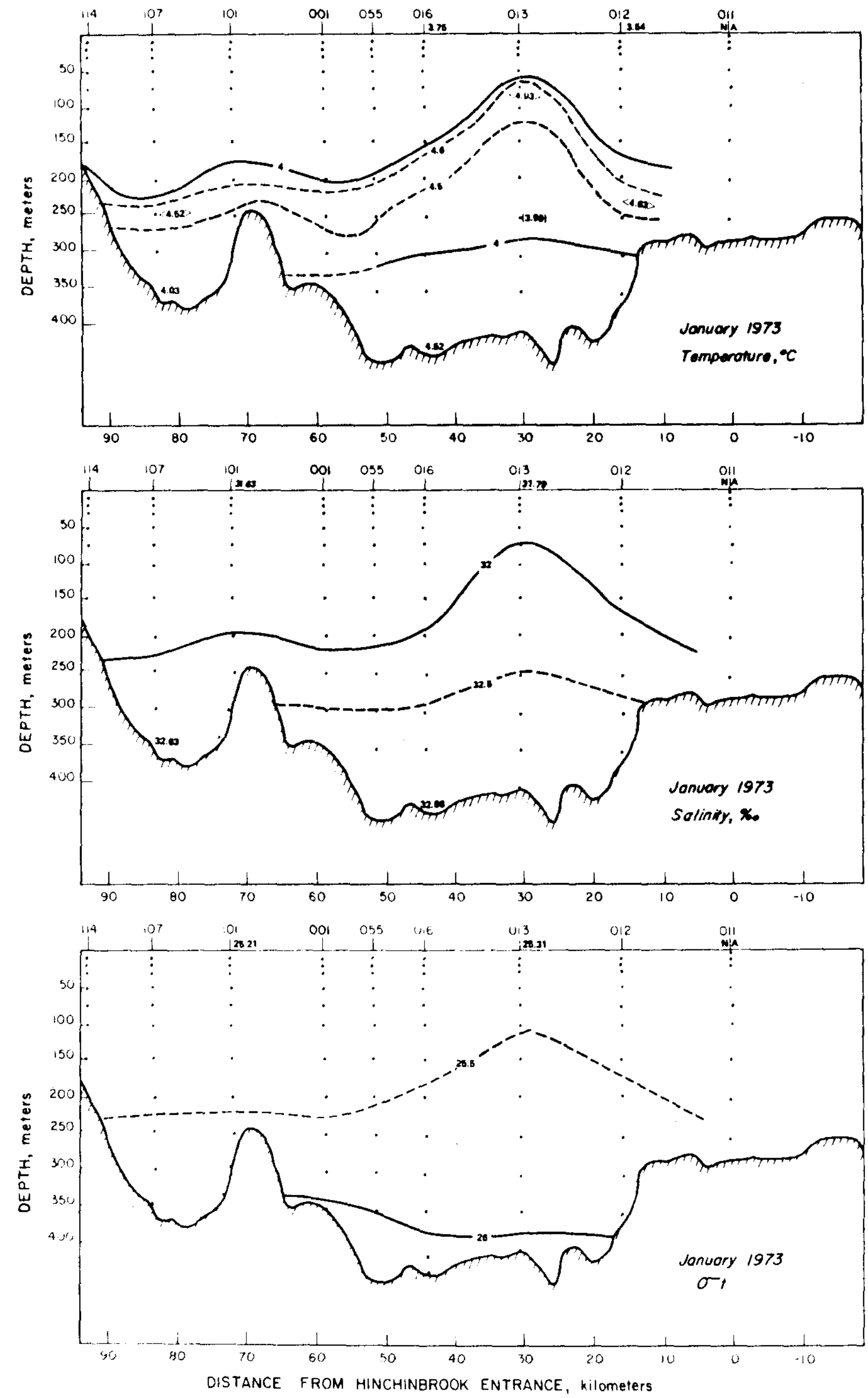


Figure J. Longitudinal hydrographic sections for January 1973.

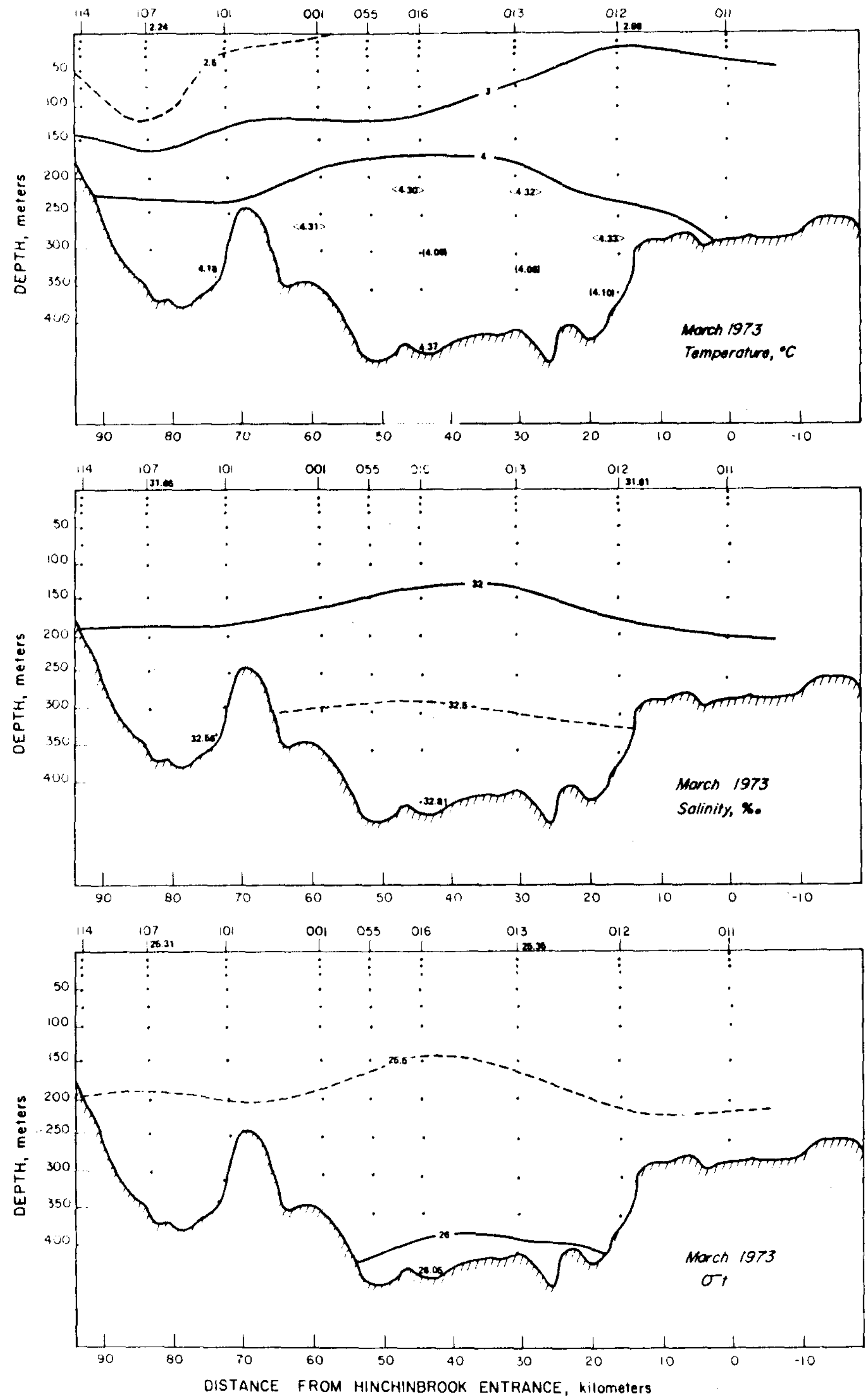


Figure K. Longitudinal hydrographic sections for March 1973.

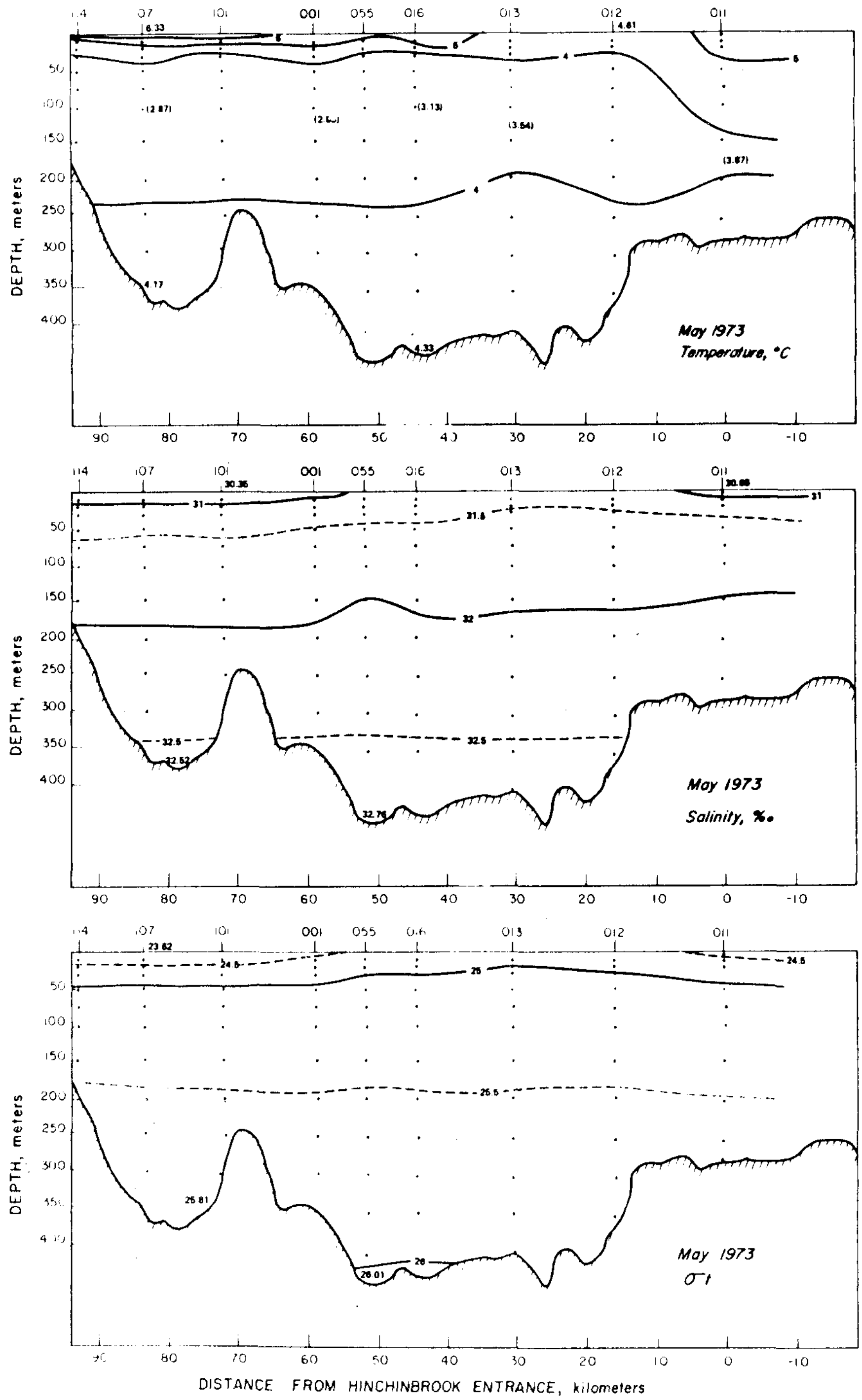


Figure L. Longitudinal hydrographic sections for May 1973.

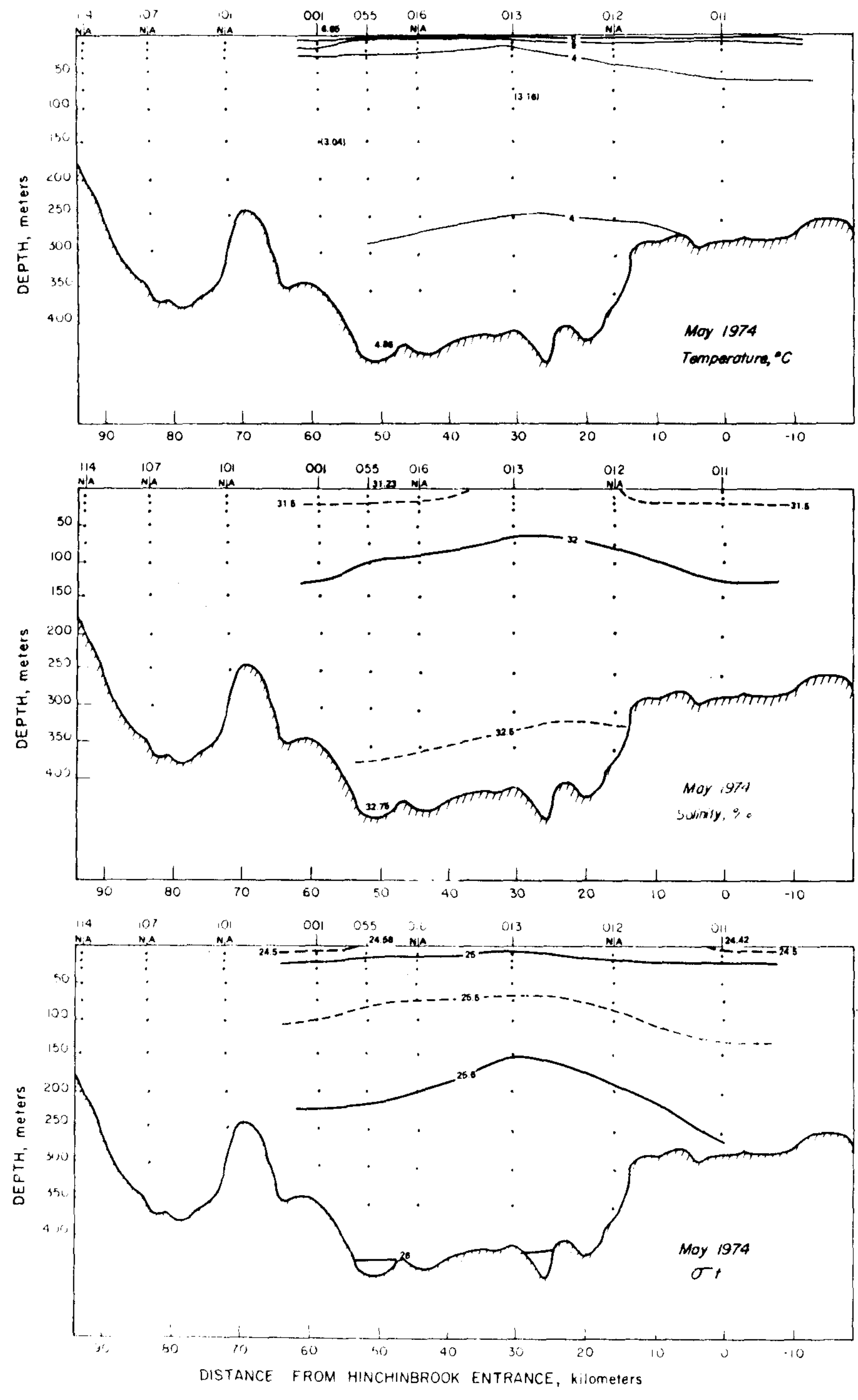


Figure M. Longitudinal hydrographic sections for May 1974.

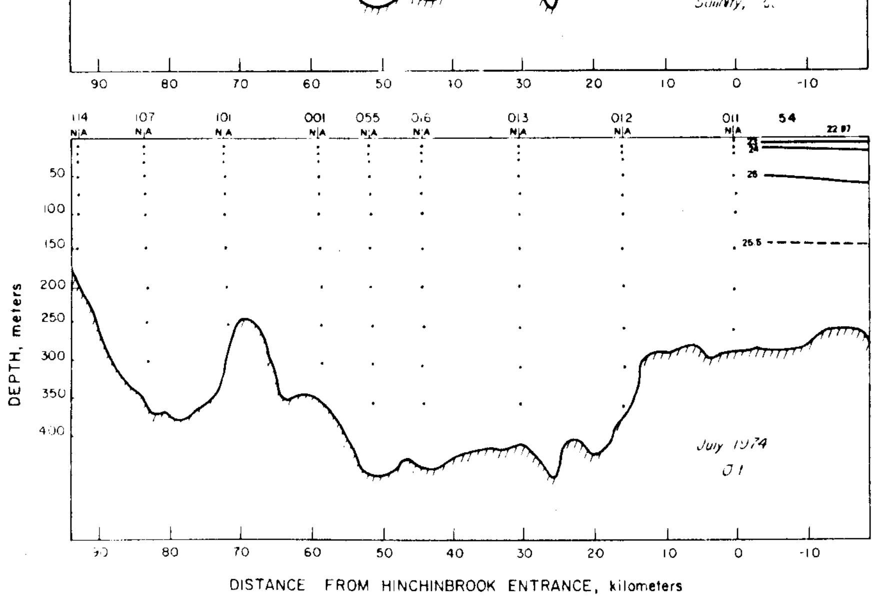
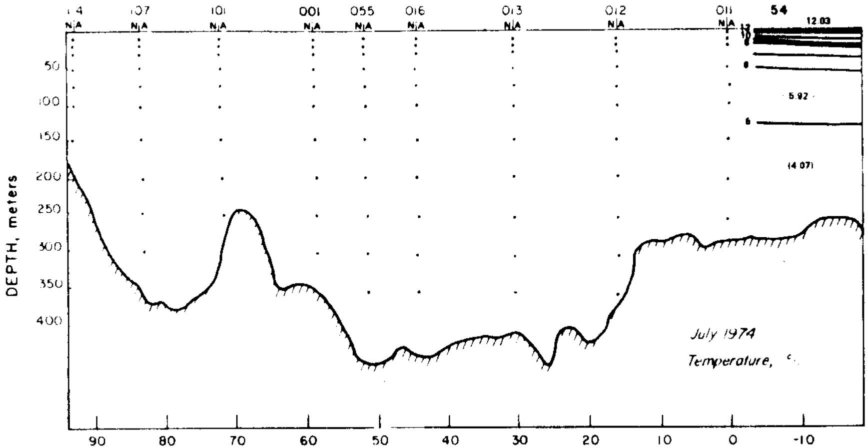
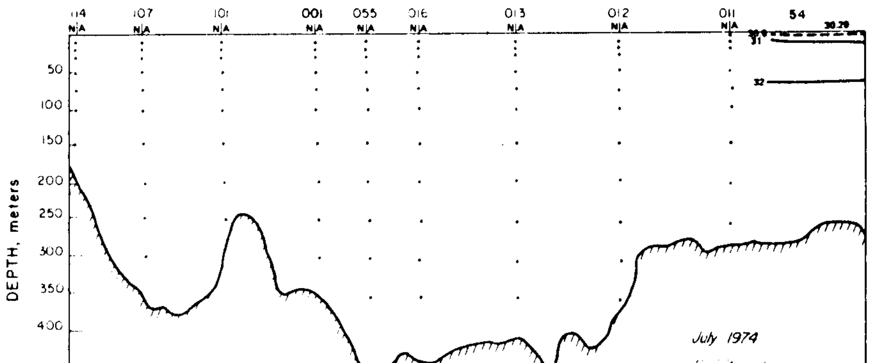


Figure N. Longitudinal hydrographic sections for July 1974.



DEPTH, meters
July 1974
Temperature, °C



DEPTH, meters
July 1974

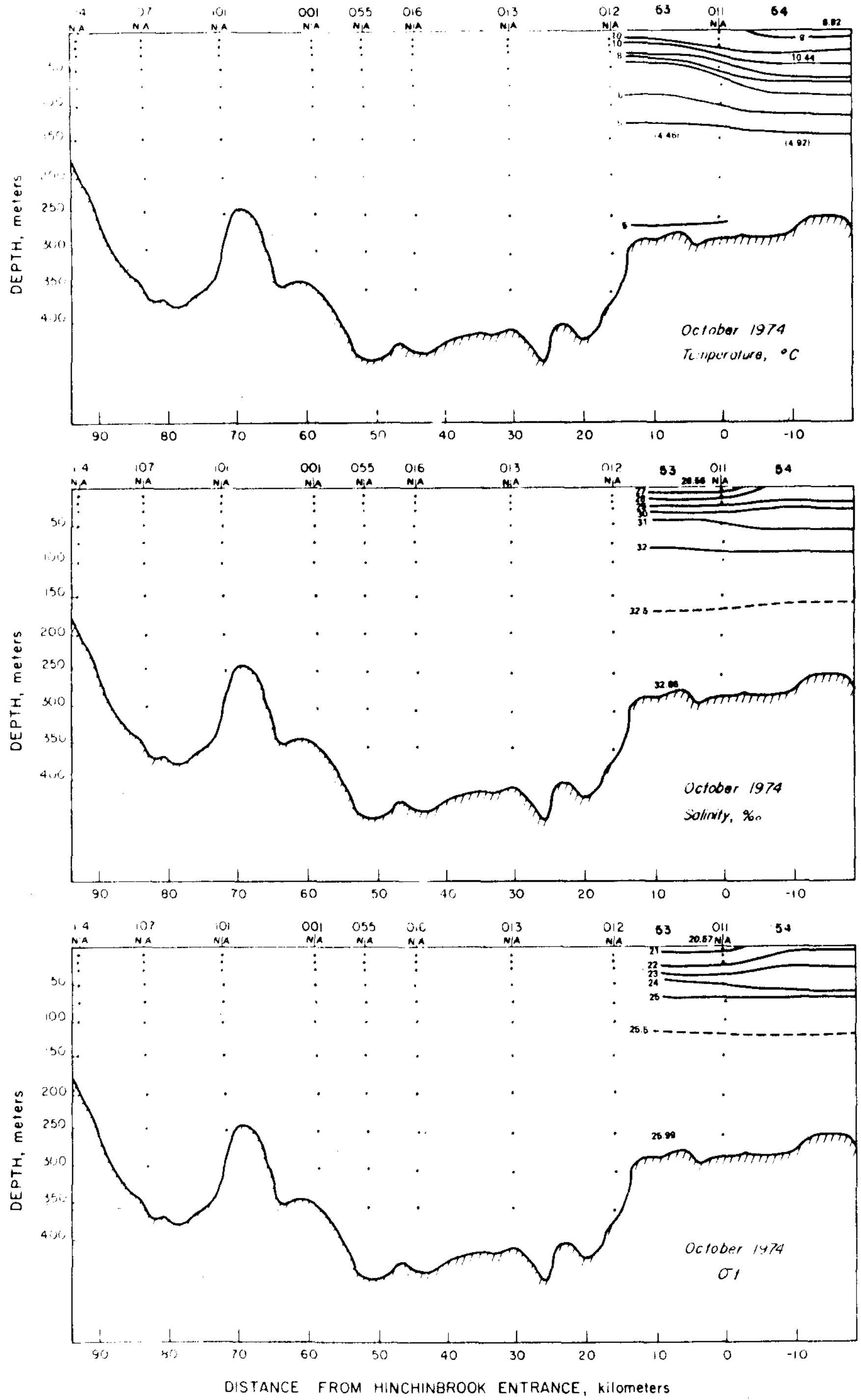


Figure O. Longitudinal hydrographic sections for October 1974.

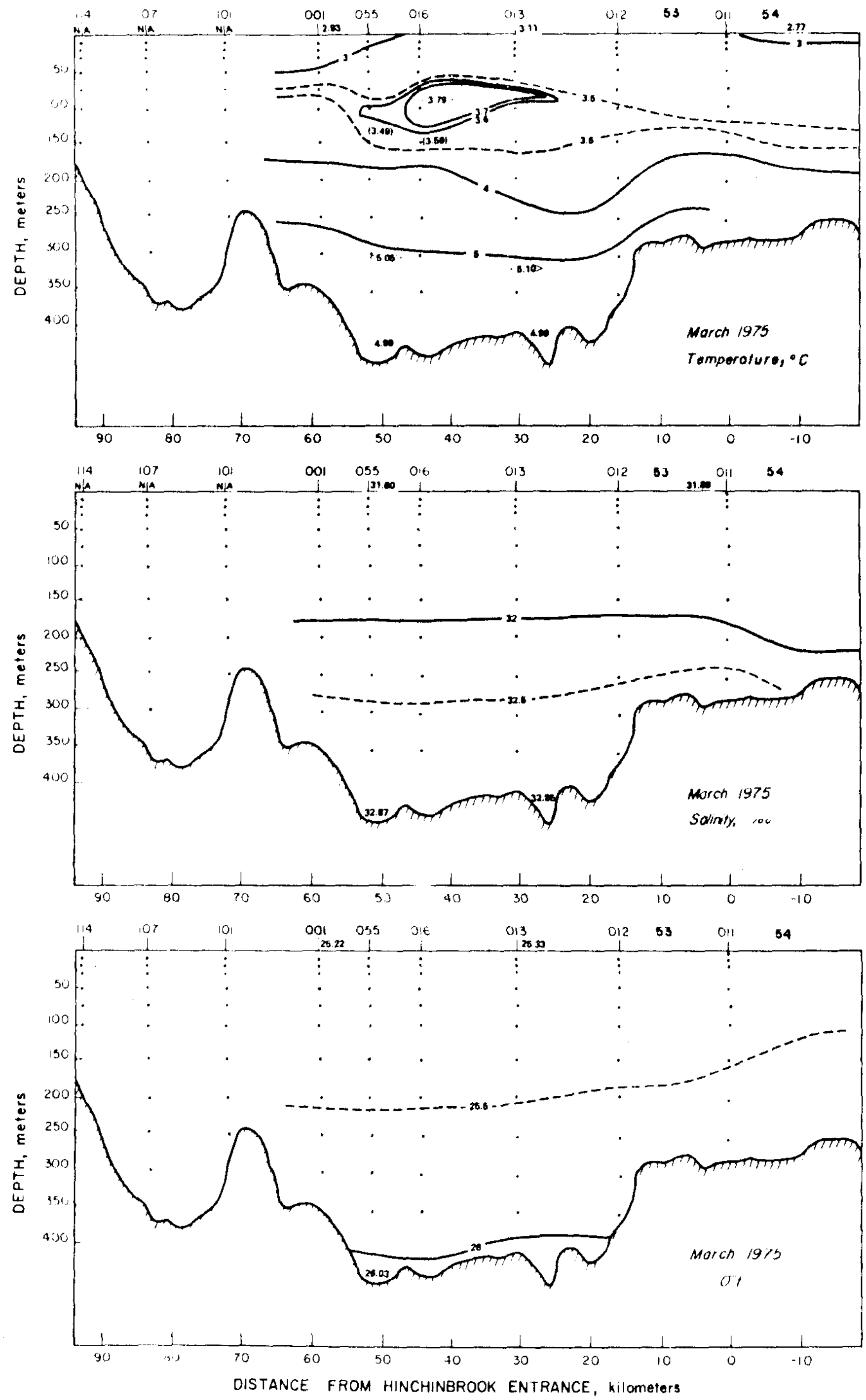


Figure P. Longitudinal hydrographic sections for March 1975.

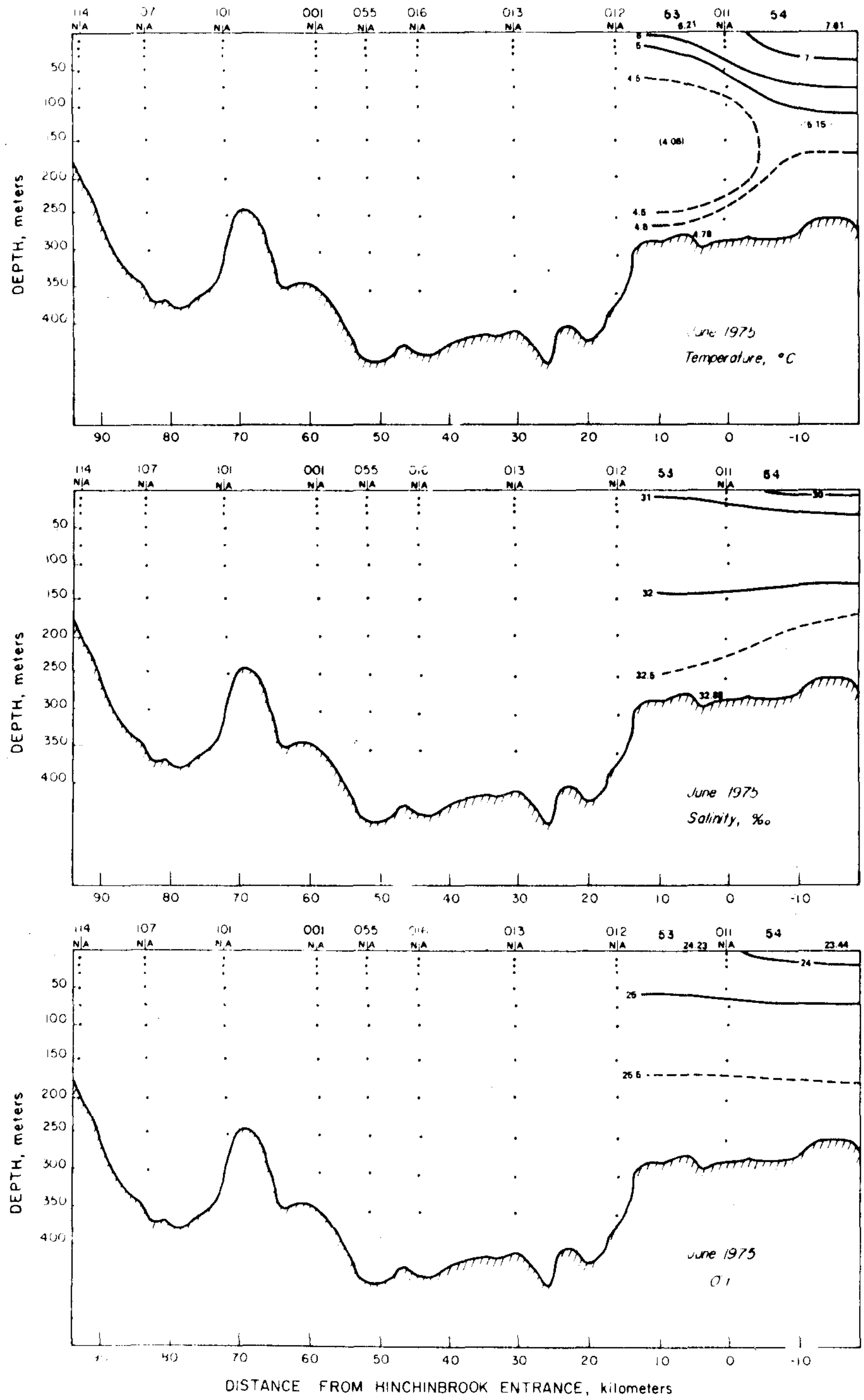


Figure Q. Longitudinal hydrographic sections for June 1975.

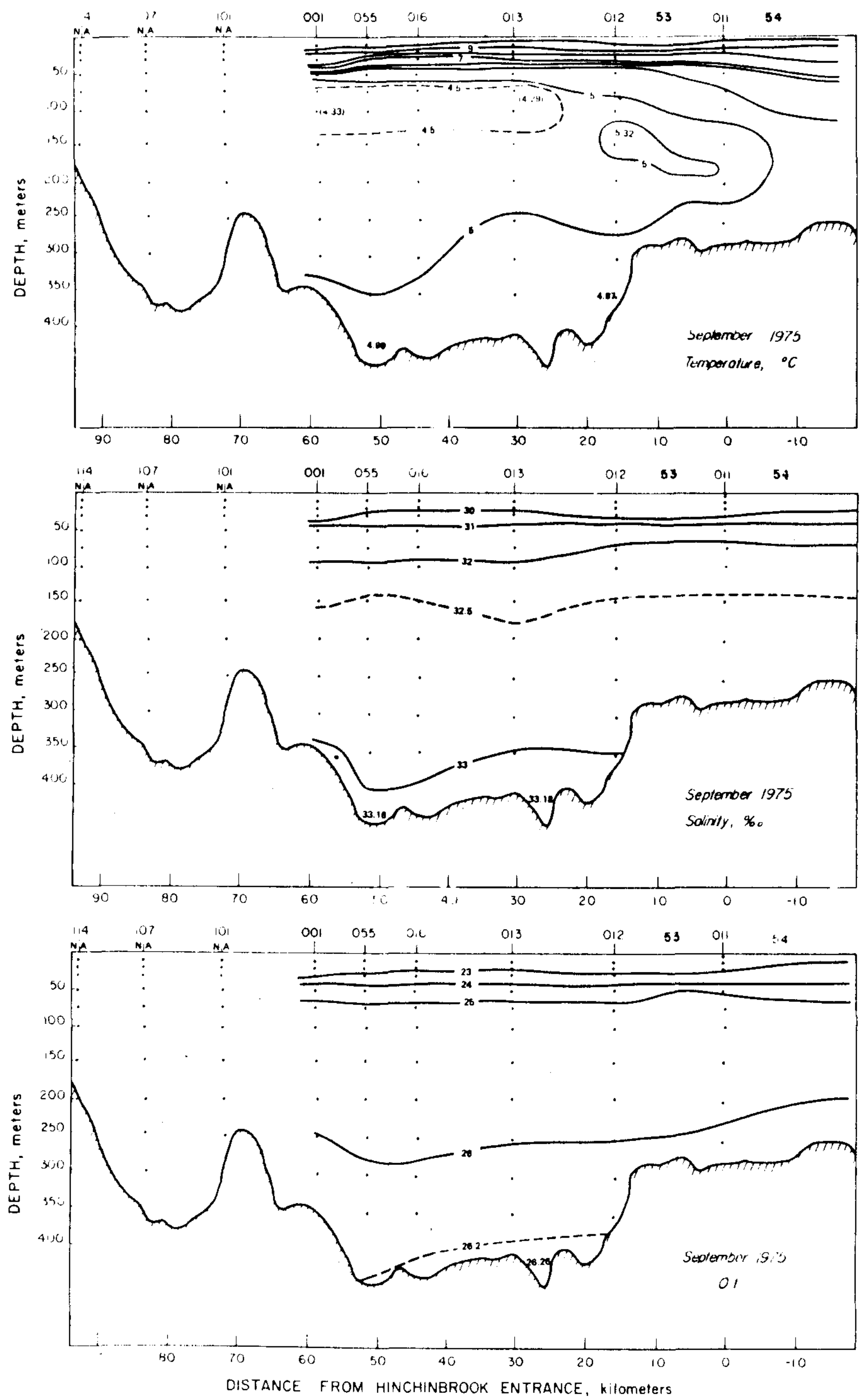


Figure R. Longitudinal hydrographic sections for September 1975.

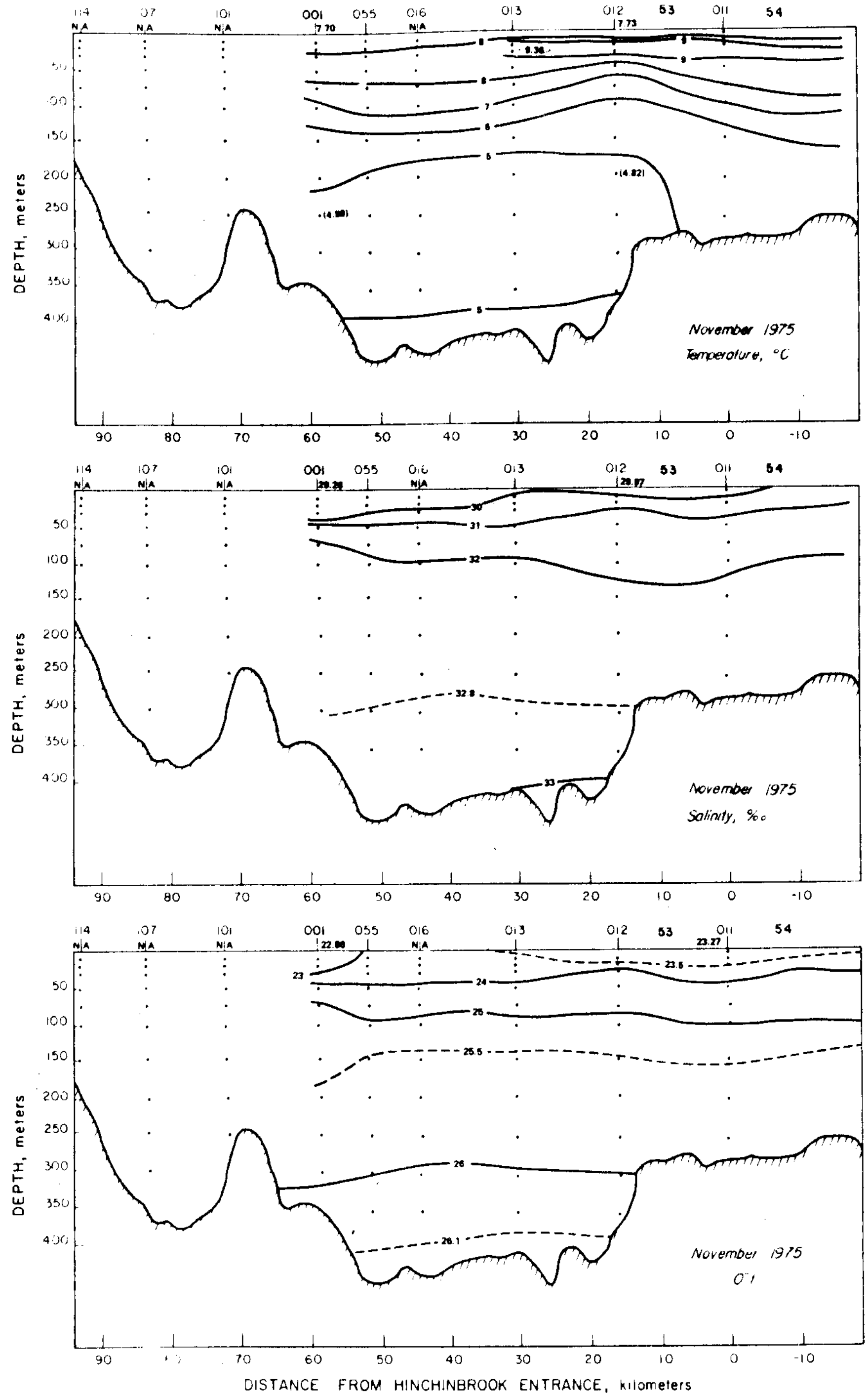


Figure S. Longitudinal hydrographic sections for November 1975.

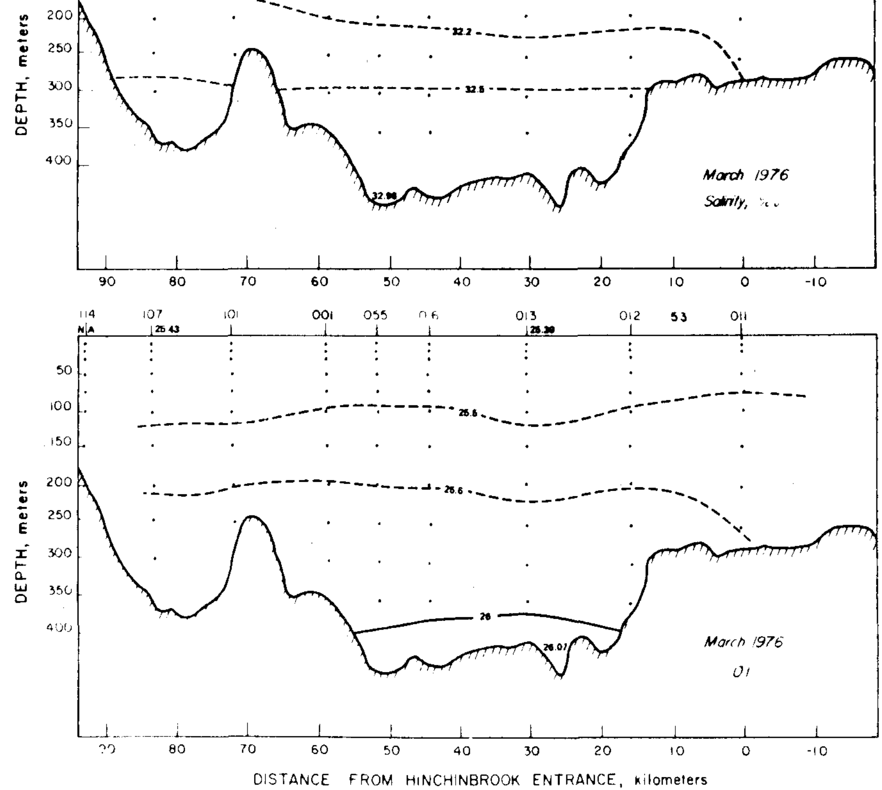
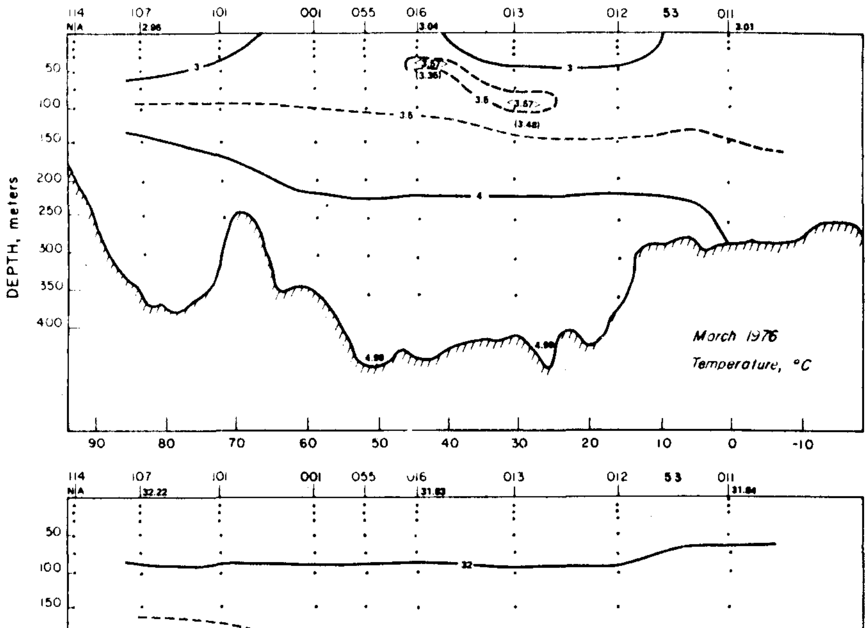


Figure T. Longitudinal hydrographic sections for March 1976.



DEPTH, meters
March 1976
Temperature, °C
114
N/A
107
101
001
055
016
013
012
53
011
2.96
3.04
3.01
3
3.6
4
3.67
3.36
3.48
4.98
32.22
31.83
31.84
32

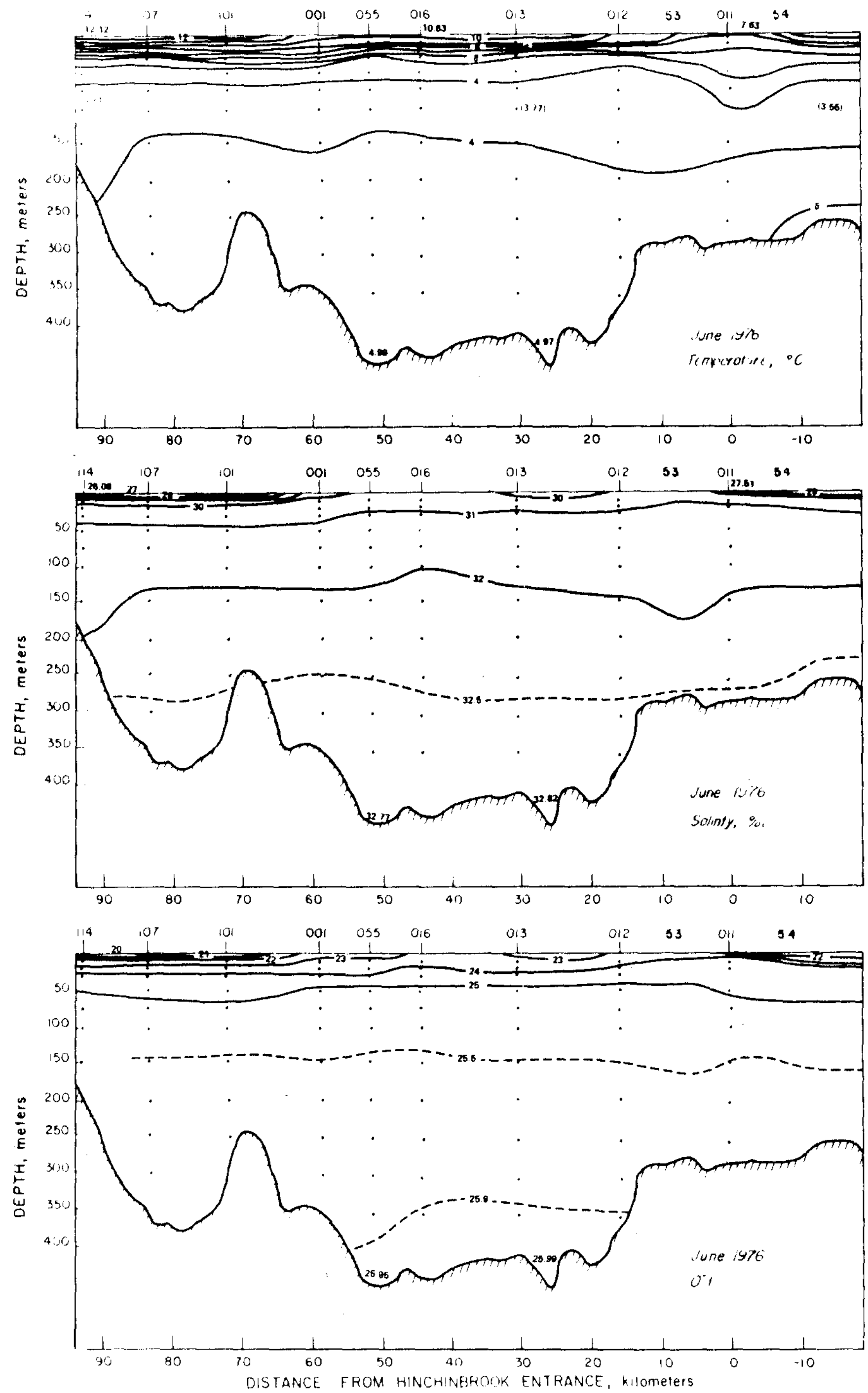


Figure U. Longitudinal hydrographic sections for June 1976.