Chapter 9

95320M Observational Physical Oceanography

1995 Annual Report
Observational Physical Oceanography in Prince William Sound and the Gulf of Alaska

Exxon Valdez Trustee Council Project 95320-M
April 1996

Shari L. Vaughan, Principal Investigator
Shelton Gay, Thea Thomas, and Loren Tuttle
Prince William Sound Science Center
Cordova, Alaska

ABSTRACT

Hydrographic surveys and current velocity measurements collected during five cruises in 1995 show significant monthly variability in the water mass properties and circulation patterns in Prince William Sound. Temperature, salinity, and potential density in March and April are shown to be fairly homogeneous. The warm, fresh Gulf of Alaska inflow is evident in the upper 20 meter layer in May and June. By September, the water entire column has warmed and become saltier. Baroclinic velocities (20/100 meter) calculated from towed ADCP transects indicate that the northern, western, and eastern portions of the sound are characterized by either weak baroclinic, or barotropic currents. An ADCP mooring at Hinchinbrook Entrance shows weak and variable currents, with mostly inflow above about 150 m and outflow below. Meteorological forcing at one station is shown to mix the water column down to about 50 meters. These measurements, combined with a numerical circulation model, will be used to define 'river' and 'lake' conditions, and to study the effect of these condition on zooplankton abundance and distribution. The goal of this project is to identify physical factors that influence the production of pink salmon and Pacific herring in Prince William Sound.

INTRODUCTION

The Sound Ecosystem Assessment (SEA) is aimed at identifying the primary factors that control the production of pink salmon and Pacific herring in Prince William Sound (PWS). A main hypothesis of SEA is that physical conditions, such as ocean temperature and salinity, flow velocities, and atmospheric forcing, primarily determine the survival of embryos and juvenile fish. Processes that control the physical environment include tidal motions, wind stress, seasonal heating and cooling, precipitation, river/glacial runoff, inflow and outflow of Gulf of Alaska (GOA) water, and longer term events like El Nino and the Southern Oscillation (ENSO). Time scales of these processes range from hours to decades, and space scales range from tens of meters to O(100 km).

The northern Gulf of Alaska (GOA) and the Alaska Coastal Current (ACC) have been studied extensively since the mid-1970's. The seasonal variations of quantities such as baroclinic geostrophic transport, wind forcing, freshwater discharge, and coastal upwelling, have been described elsewhere (e.g. Royer and Emery, 1987; Johnson et al, 1988; Royer, 1981a,b; Royer, 1979). Several of these papers mention interactions of the ACC with PWS (e.g. Royer et al, 1979; Royer et al, 1990), but attention to the Sound was usually brief.

Niebauer et al (1994) presented the first description of the circulation and water mass properties of PWS, based on data collected between 1974 and 1989. They focused on two periods: 1977-1979, and 1989 (after the Exxon-Valdez oil spill). Hydrographic data were used to created dynamic topographies (0/100 m), and to calculate monthly means of baroclinic geostrophic transport (relative to 100 m) at Hinchenbrook Entrance and Montague Straight. Current meter moorings were deployed over 15 months from 1977 to 1979 in both Hinchenbrook Entrance and Montague Straight. Current velocities (20 m values minus 100 m values) from acoustic Dppler current profiler (ADCP) transects made in 1989 were also presented. Based on estimates of transports in various pressure layers, and estimates of the total volume of the layer, Niebauer et al made estimates of flushing rates of PWS. The concluded that about 40% of PWS was flushed from May through September, and that the Sound was flushed about two to four times from October to April.

Results presented here describe some of the spatial and temporal variability of the large scale circulation and water mass properties of PWS observed in 1995. Basin scale hydrographic surveys, and ADCP transects were conducted on five cruises in 1995. An upward looking ADCP mooring deployed in Hinchenbrook Entrance collected data simultaneously. Two C-MAN stations in PWS collected meteorological data from May to December 1995. The physical measurements presented here may be correlated with the meteorological measurements, and with the biological measurements presented elsewhere in this report. These results demonstrate the monthly variability of the circulation and water mass properties of PWS. Combined results from 1994, 1995, and subsequent field years will be used to create estimates of seasonal mean properties, which will then be used to validate the numerical circulation model described in Chapter 95320-J.

DATA

Large scale oceanographic cruises were conducted in March, April, May, June, and September of 1995. The station locations for the April cruise is shown in Figure 1 as an example. Not all stations were occupied in all cruises, but the spatial coverage was about the same. The cruise dates are listed below.

March	15-23
April	10-17
May	4-11
June	15-20
Sept./Oct.	29- 3

The hydrographic data was collected using a SeaBird 911 CTD. Conductivity, temperature, and pressure (depth) were recorded at 1 dbar intervals. Salinity was calculated from conductivity using standard SeaBird software. The CTD salinities were not calibrated with bottle samples.

Instantaneous current velocity transects were collected using an RDI 150 kHz broadband ADCP deployed from the stern of the ship in a towed body. Most transects were in water less than 400 m depth so that bottom tracking was available. The bin length was 8 m for most of the data. The ADCP generally measured flows from about 20 m depth to the bottom. Some transects were repeated in more than one cruise, but most were made on an opportunistic basis, generally between hydrographic stations.

A time series of current velocities as a function of depth was collected from an upward looking ADCP mooring (RDI 150 kHz broadband) deployed in Hinchenbrook entrance from mid-June to late September, 1995. Velocities were recorded every 30 minutes using an 8 m bin length. Good velocities were obtained from 43.5 m to about 300 m depth.

Meteorological data from C-MAN stations in PWS are available from the National Data Buoy Center (NDBC). The stations are located at Bligh Reef, Potato Point, Seal Rocks, and Mid-Sound (in the central Sound). Wind speed, wind direction, wave height, barometric pressure, air temperature, water temperature, dew point temperature, and visibility are measured every 30 minutes. The buoys became operational in May 1995, and have collected mostly uninteruped data since then.

Plankton data was obtained from 5 months in 1995 from a towed optical plankton counter (OPC). Some of the OPC cruises were not simultaneous with those listed above. The OPC was mounted together with a Chelsea Instruments CTD (the Aquapak) in an Aquashuttle tow body and deployed from the ship. The combined package cycled vertically from the surface to about 80 m depth.

ANALYSIS

Hydrography

Average values of temperature and salinity were calculated over several depth layers and contoured using GMT version 3 programs (Wessel and Smith, 1995). Examples from May and September 1995 are shown in Figures 2 and 3. Contours of temperature and salinity averaged over the upper 20 meters from May show the intrusion of the warmer, fresher GOA water on the east side of Hinchenbrook Entrance (Figure 2). This intrusion is still present in June (not shown). By September, this water mass contrast is no longer apparent; the layer is cooler and fresher in the north.

Mean temperature and salinity calculated over the 90 to 110 m layer in September 1995 are contoured in Figure 3. Warmer, saltier water outside Hinchinbrook Entrance does not appear to have entered PWS at this depth. A fairly strong temperature gradient exists in this layer between PWS and the GOA.

Potential density was calculated from the temperature and salinity measurements at each station, and averaged over the upper 100 meters. Contours of mean potential density for each cruise are presented in Figures 4(a)-(e). In March and April (Figures 4(a),(b)), this layer is fairly uniform (the contouring interval is .05). By May (Figure 4(c)), the sound has started to stratify zonally (the contouring interval is .1). A mid-Sound (147 W) density gradient between the lighter inflowing GOA water in the east, and a small dense region to the north of Montague Island is present in May. By June (Figure 4(d)), the layer is fairly uniform east of 147 W, but the relatively dense region north of Montague Island persists. By September (Figure 4(d)), the layer density gradients are stronger (the contouring interval is .2) and more symmetric, with the highest densities in the center of the central basin.

To illustrate the monthly variations in vertical stratification, temperature, salinity, and potential density profiles from repeat occupations of the CFOS13 station located in the central sound, are presented in Figures 5(a)-(e). The March potential density (sigma) profiles shows the water column to be completely mixed down to about 200 m (Figure 5(a)). The April salinity profile shows a slight freshening above about 100 m (Figure 5(b)). The April (Figure 5(b)) and May (Figure 5(c)) salinity and sigma profiles are almost identical. Significant warming and freshening has occured by June (Figure 5(d)), but the changes are confined to the upper 100 m. Below 100 m the potential density (sigma) is unaffected. By September (Figure 5(e)), warming has occured at all depths. The September salinities are fresher at the surface (< 15 m) than in June, but at depths greater than 15 m, salinities are greater. Potential density also is less at the surface than in June, and greater below 15 m.

ADCP Transects

Current shear velocities at 20 m relative to 100 m for each cruise are presented in Figure 6(a)-(e). The shear velocities are calculated by subtracting the 100 m velocities from the 20 m velocities. Flow velocities measured by the towed ADCP include a tidal component, and the time for completion of many of the transects covered a large portion of the tidal cycle. Velocities at 20 m relative to 100 m were calculated to eliminate the contribution from the barotropic tide. Neibauer et al (1994) also presented shear velocities over this layer (20/100 m) from data collected in 1989.

Subtracting velocities from two different levels also eliminates any barotropic (vertical mean) component of the flow, along with the tidal component. The vectors in Figure 6 represent the baroclinic (shear) component (the difference in velocities from 20 to 100 m), not necessarily the velocity of the flow. A small shear velocity may result from slowly moving currents at both 20 and 100 m, or from a strong barotropic current (currents of equal magnitude at both 20 and 100 m). If the velocity at 100 m was equal to zero, the vectors in Figure 6 would represent the speed and direction of the flow at 20 m. Vertical sections of ADCP transects show that velocities at 100 m are sometimes not negligable, and are often opposite in sense to those at 20 m. Individual transects must be inspected for the sense and magnitude of the 100 m velocities before conclusions are made about the actual large scale circulation.

In most cruises, the baroclinic velocities are strongest (> 50 cm/sec) at Hinchinbrook Entrance, and and the central sound. Shear velocities north of about 60.7 N (Naked Island), east of about 146.7 W (Knowles Head), and in the western sound (Knight Island Passage and west of Green Island) are generally weaker (although the barotropic component could be strong). This is especially true in May (Figure 6(c)), June (Figure 6(d)), and September (Figure 6(e)), and to a lesser extent in April (Figure 6(b)). The March cruise is an exception. Velocity shears are weakest in the central sound. Strong shears exist outside of Hinchinbrook Entrance in the GOA, in Montague Straight, and in the northwest Sound, south of Ester Island.

ADCP transects were made across Hinchinbrook Entrance on all but the September cruise. Repeat transects were made in May (not shown). The flow was mostly north in March over all depths (barotropic), and mostly southwest in April. Repeat transects in May indicated that the velocities were primarily tidally driven. The velocities were barotropic, and shifted from mostly north to mostly south over approximately a 12 hour period. In June, the velocities across Hinchinbrook Entrance were much less than earlier in the year, and showed considerable vertical structure (baroclinic). The flow was mostly toward the north, with much higher velocities on the eastern side of the Entrance.

ADCP Mooring at Hinchinbrook Entrance

North and east velocity components from an upward looking ADCP mooring in Hinchinbrook Entrance are shown in Figures 7(a) and (b). The velocities represent daily (24 hour) means. Negative velocities (south and west) are shaded. The upper depth bin was centered at 43.5 m. The mooring was deployed from June 22 to September 30, 1995 (julian day 173 to 272).

Above about 150 m, velocities are mostly less than 10 cm/sec toward the southwest. Deeper velocities reach speeds of 15 cm/sec, and alternate between north and south directions. Further analysis is needed to determine if the alternating pattern is an artifact of the averaging (higher frequency components aliased into the daily means), or a real feature of the circulation.

Weekly (7 day) mean velocities were also calculated and contoured (not shown). East velocities were mostly negative (west) and less than 5 cm/sec down to about 200 m. The flow was mostly to the south above 150 m and to the north below. Velocity magnitudes were between 5 and 10 cm/sec.

Meteorological Data

Time series of wind speed and direction were created for the PWS C-MAN stations located at Seal Rocks and in the central sound (Mid-Sound). Mid-Sound winds from September and October are shown in Figures 8(a) and (b). Strong wind events occurred around September 18 (hour 504 in Figure 8(a)), and October 1 (hour 24 in Figure 8(b)). Winds from May to September were mostly less than 10 m/s at both locations.

To examine the effects of wind forcing on vertical stratification, profiles of temperature, salinity, and potential density (sigma) were created for a station in the central sound (NS3) occupied on October 3 (during the September cruise) after the strong October wind event (Figure 9). These profiles may be compared with those of a nearby station (CFOS13) occupied during the same cruise on September 29, before the wind event (Figure 5(e)). After the wind forcing, the temperature at NS3 was uniform down to about 50 m, and is warmer than before the forcing down to about 100 m. Salinities are fresher to about 100 m, and are less than 26 at the surface. Potential densities are decreased as a result of the warming and freshing, down to about 100 m, although differences are small below about 60 m. Below 100 m, all profiles are virtually the same. Between about 10 and 60 meters, the stratification is considerably weaker after the wind forcing.

Plankton Data

An example of OPC data collected in April 1995 from Hinchinbrook Entrance to Valdez Arm is shown in Figure 10. High numbers of neocalanus (or neocalanus sized scatterers) is shown by the light colored region north of Hinchinbrook Entrance from about 5 to 30 meters depth. This high density patch extends from Hinchinbrook Entrance (about 60.25) to about 60.6 N, or roughtly 40 km. A similar plot of total counts (not shown) suggests that the water column down to 80 m was filled with scatterers of various sizes (plankton and others).

ADCP baroclinic velocities (20/100 m) from April 1995 (Figure 6(b)) in the region corresponding to the zooplankton patch are weaker than at Hinchenbrook Entrance, or farther north in the central sound. North of the patch, the velocities at 20 m are greater in the southerly direction than velocities at 100 m. Contours of temperature and salinity averaged over the upper 20 meters from April (Figure 11) show a relatively warm, salty region at the patch location. A zonal density front centered at about 60.5 N separates the warm, salty region from the rest of the Sound. Whether the location and extent of the neocalanus patch is related to the current velocities at 20 m, or to a particular water mass is uncertain.

DISCUSSION

The potential density contours in Figures 4(a)-(e) may be used to make some inferences about the sense of the baroclinic (shear) velocities in this layer. The thermal wind relationship (based on geostrophic and hydrostatic balance) states that horizontal gradients in density are balanced by the vertical gradient of velocity (vertical velocity shear). The horizontal gradients of mean density of the 0 to 100 m layer (Figure 4) are proportional to the difference between the velocities at 0 and 100 m (shear). If the horizontal density gradient is zero, then the baroclinic component of the flow is zero, but the barotropic component may be non-zero. A barotropic current (constant with depth) could exist in the absence of a horizontal density gradient. In some cases, ADCP transect current data indicate that the velocity at 100 m is much smaller that the velocities above, so that the horizontal density gradients may be interpreted as proportional to the speed and direction of the actual flow (not just the baroclinic component). In other cases, the 100 m velocities are not negligable, and the relationship is more complex.

The density contours in May (Figure 4(c)) and June (Figure 4(d)) show a region of increased density north of Montague Island. Assuming thermal wind balance, this pattern is consistent with a cyclonic (counterclockwise) baroclinic flow. The velocities would be increasing from 100 m to the surface in the cyclonic direction. The weak horizontal density gradients in the eastern sound (east of 147 W) especially in June, indicate the absense of a baroclinic flow. Currents from Hinchinbrook Entrance north could be barotropic.

The density contours in September (Figure 4(e)) show a maximum density in the central sound. This pattern is consistent with a cyclonic baroclinic circulation in the central basin. Without knowing the flow velocities at 100 m, it is impossible to determine the magnitude and sense of the actual circulation. The density contours in September indicate only that from 100 m to the surface the current velocity is increasing cyclonically.

The results presented here may be compared with those of Niebauer et al (1994). Maps of 0/100 dbar dynamic topography from June 1976 and September 1978 (their Figure 7) are used to infer the large scale circulation pattern in the Sound. They state that the June 1976 dynamic heights 'hints' at the inflow through Hinchinbrook Entrance and cyclonic interior circulation. The closed contours in the central sound in September 1978 also suggest a cyclonic circulation similar to that indicated in September 1995.

Light and variable current velocities from the ADCP mooring at Hinchinbrook Entrance are consistent with the results of Niebauer et al (1994). A current meter mooring with instruments at 50, 100, 200, and 320 m recorded velocities in Hinchinbrook Entrance from June through September 1978. From 50 to 200 m, flows were generally around 10 cm/sec in no preferred direction, with occasional bursts to 25 cm/sec or greater. Only at the 320 m level were strong (> 25 cm/sec) northward velocities observed during this period. Strong (> 50 cm/sec) northward velocities were observed in the upper levels (30 and 50 m) starting in October (Niebauer et al, 1994).

CONCLUSION

Characteristics of the large scale water mass properties and circulation of PWS in March, April, May, June, and September, 1995 have been briefly described. Considerable variability in the spatial temperature and salinity structure exists between months. The sound is nearly homogeneous in March and April. Intrusions of GOA water is first evident in the upper 20 m layer in May, and remains present in June. By June, warming and freshening has occurred in the upper 100 m. Below 100 m, the water column is still weakly stratified. By September, the entire water column has been modified. Temperature and salinity were greater at all depths, except for a fresh layer at the surface. In all profiles, the density seems to be governed primary by salinity.

Current velocities also vary throughout the sound between March and September. Baroclinic current velocities were presented to illustrate the seasonal changes in circulation without the effects of tides. The flow in the northern, western, and eastern Sound is either weak or mostly barotropic. Current velocities at Hinchinbrook Entrance were shown to be weak and variable over the June to September period. The upper 150 m at Hinchinbrook Entrance was dominated by outflow. Below 150 m, alternating inflow and outflow was present.

Wind forcing from one brief event in October was shown to affect the vertical stratification down to about 60 m. The mixing was sufficient to remove the thermocline in the upper 50 m, but not the halocline. Some freshening was present down to about 100 m. With the NDBC C-MAN meteorological buoys in place, further investigation into the relationship between longer wind events, vertical stratification, and current velocities will be possible.

The results presented here represent work in progress. Future efforts are aimed at using the hydrographic and current velocity data to define 'river' and 'lake' conditions, and to study the effect of these condition on zooplankton abundance and distribution. The 1995 data will be combined with SEA data from 1994 and 1996, and with historical data, to make estimates of seasonal means and seasonal variability. The seasonal mean properties, along with the flow velocities at Hinchinbrook Entrance, will be used to verify and refine the numerical cirulation model of PWS.

ACKNOWLEDGEMENTS:

James Murphy (formerly at PWSSC) prepared the ADCP velocity transect figures, and post-processed the ADCP mooring data. Steve Bodnar (PWSSC) located and downloaded the meteorological data from NDBC. The software used to generate the OPC figure was developed by Eddy Jin (UAF).

REFERENCES

Johnson, W.R., T.C. Royer, and J.L Luick, 1988: On the Seasonal Variability of the Alaska Coastal Current. J. Geophy. Res., 93, 12,423-12437.

Niebauer, H.J., T.C. Royer, and T.J. Weingartner, 1994: Circulation of Prince William Sound, Alaska. J. Geophys. Res., 99, 14,113-14,126.

Royer, T.C., 1979: On the Effect of Precipitation and Runoff on Coastal Circulation in the Gulf of Alaska. J. Phys. Oceanog., 9, 555-563.

Royer, T.C., 1981a: Baroclinic transport in the Gulf of Alaska Part I. Seasonal variations on the Alaska Current. J. Mar. Res., 39, 239-249.

Royer, T.C., 1981b: Baroclinic transport in the Gulf of Alaska Part II. A fresh water driven coastal current. J. Mar. Res., 39, 251-265.

Royer, T.C., and W.J. Emery, 1987: Circulation in the Gulf of Alaska, 1981. Deep-Sea Res., 34, 1361-1377.

Royer, T.C., D.V. Hansen, and D.J. Pashinski, 1979: Coastal Flow in the Northern Gulf of Alaska as Observed by Dynamic Topography and Satellite-Tracked Drogued Drift Buoys. J. Phys. Oceanog., 9, 785-801.

Royer, T.C., J.A. Vermersch, T.J. Weingartner, H.J. Niebauer, and R.D. Muench, 1990: Ocean Circulation Influencing the Exxon-Valdez Oil Spill. Oceanography, 3, 3-10.

Wessel, P., and W.H.F. Smith, 1995: The Generic Mapping Tools (GMT) version 3.0 Technical Reference & Cookbook, SOEST/NOAA.

LIST OF FIGURES

Figure 1: Hydrographic (CTD) station names and locations for the April 1995 cruise.

Figure 2: Temperature and salinity averaged over the upper 20 m for May 1995.

Figure 3: Temperature and salinity averaged over the 90 to 110 m layer for May 1995.

Figure 4: Potential density averaged over the upper 100 m for (a) March, (b) April, (c) May, (d) June, and (e) September, 1995. Station locations are shown as dots.

Figure 5: Vertical profiles of temperature, salinity, and potential density (sigma) at station CFOS13 located in central PWS for (a) March, (b) April, (c) May, (d) June, and (e) September, 1995.

Figure 6: Baroclinic velocities (20/100 meters) calculated from towed ADCP transects for (a) March, (b) April, (c) May, (d) June, and (e) September, 1995.

Figure 7: Velocity time series, (a) north and (b) east component, from the ADCP mooring at Hinchinbrook Entrance from June 22 to September 30, 1995 (julian day 173 to 272). Negative values are shaded.

Figure 8: Time series of wind speed and direction from the Mid-Sound NDBC C-MAN buoy located in central PWS for (a) September and (b) October. The time axis (Hours) are hours in each month (720 hours is 30 days).

Figure 9: Vertical profiles of temperature, salinity, and potential density (sigma) at station NS3 located in central PWS occupied on October 3, 1995, just after a period of increased winds.

Figure 10: OPC transect from Hinchinbrook Entrance to Valdez Arm in April 1995 showing counts/sec of Neocalanus as a function of depth.

Figure 11: Temperature and salinity averaged over the upper 20 m for April 1995.

Figure: 1

CTD Stations - be504

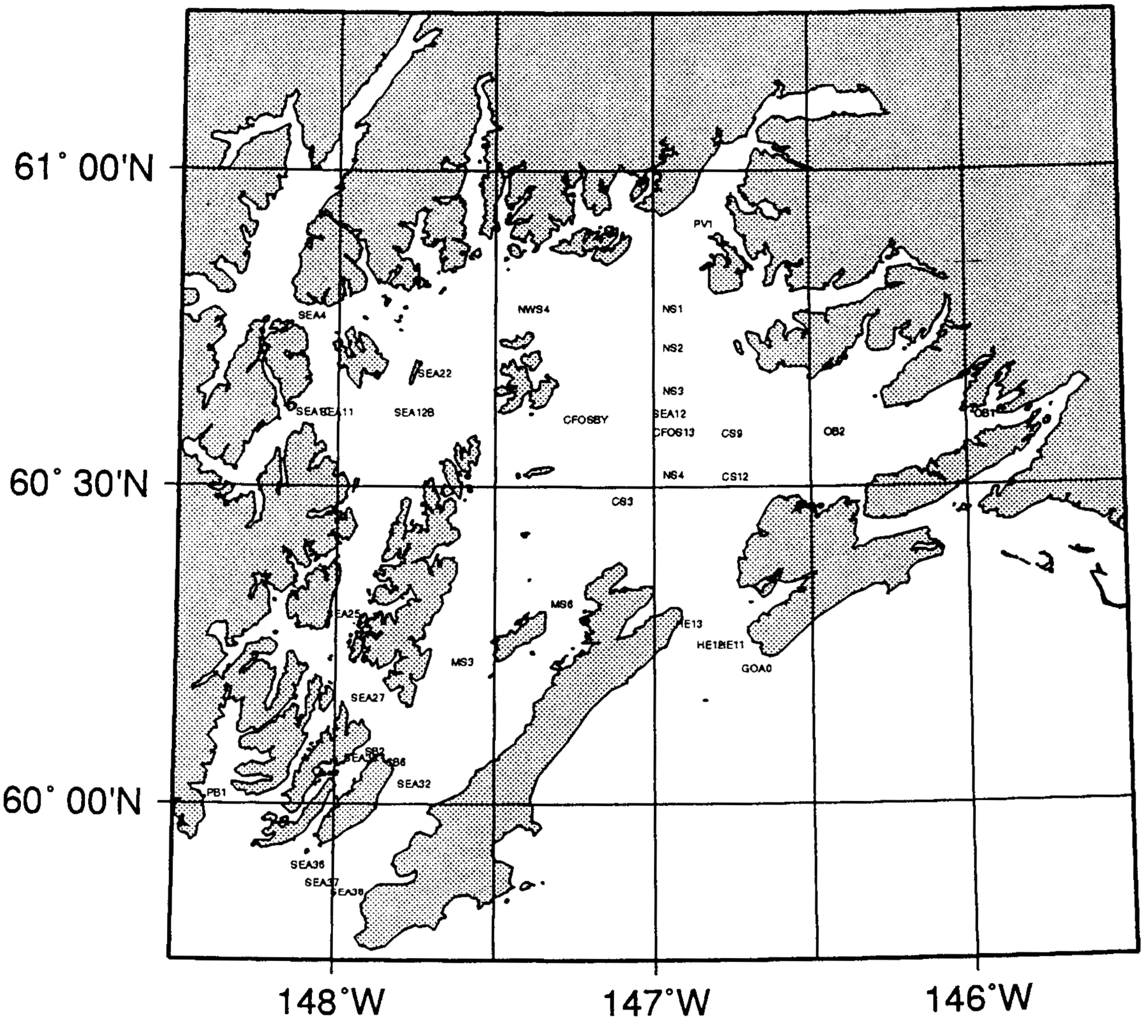
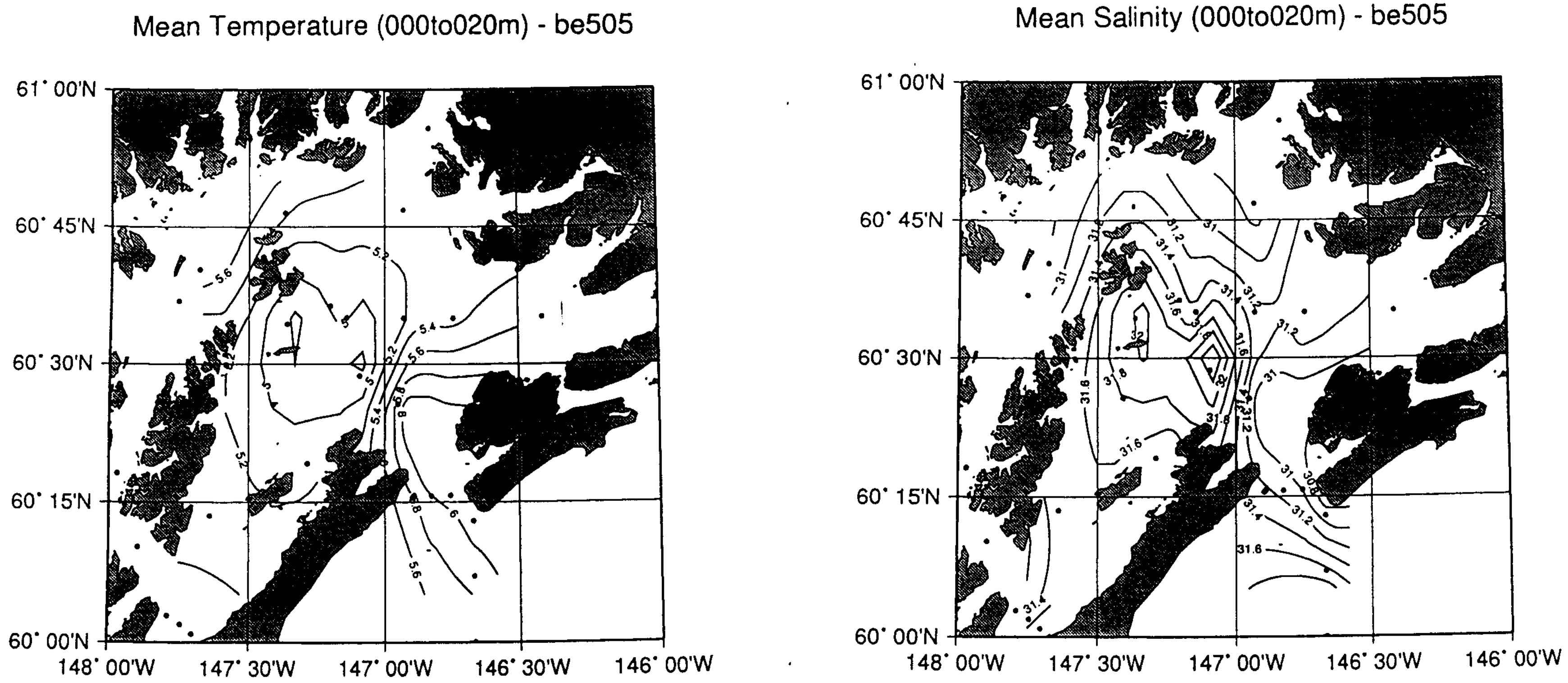


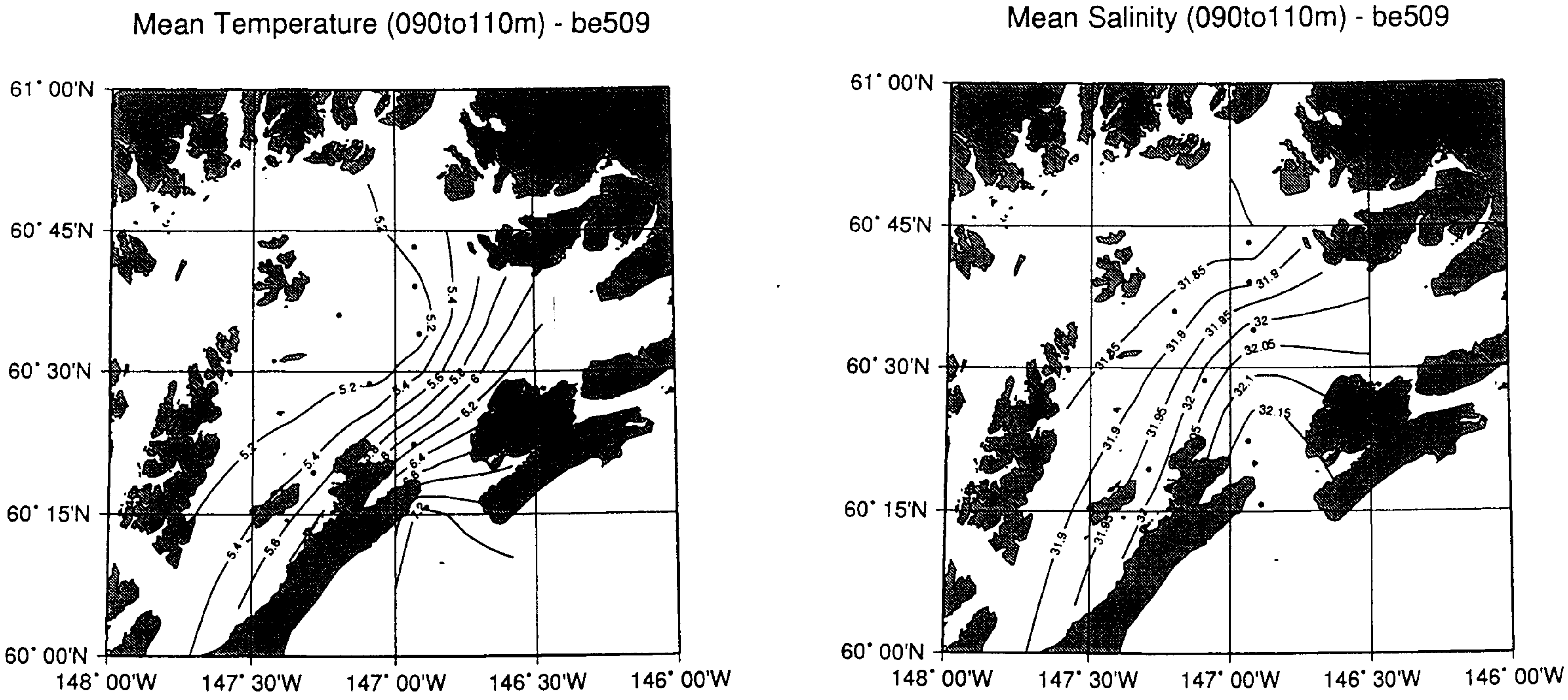
Figure: 2



Mean Temperature (000to020m) - be505

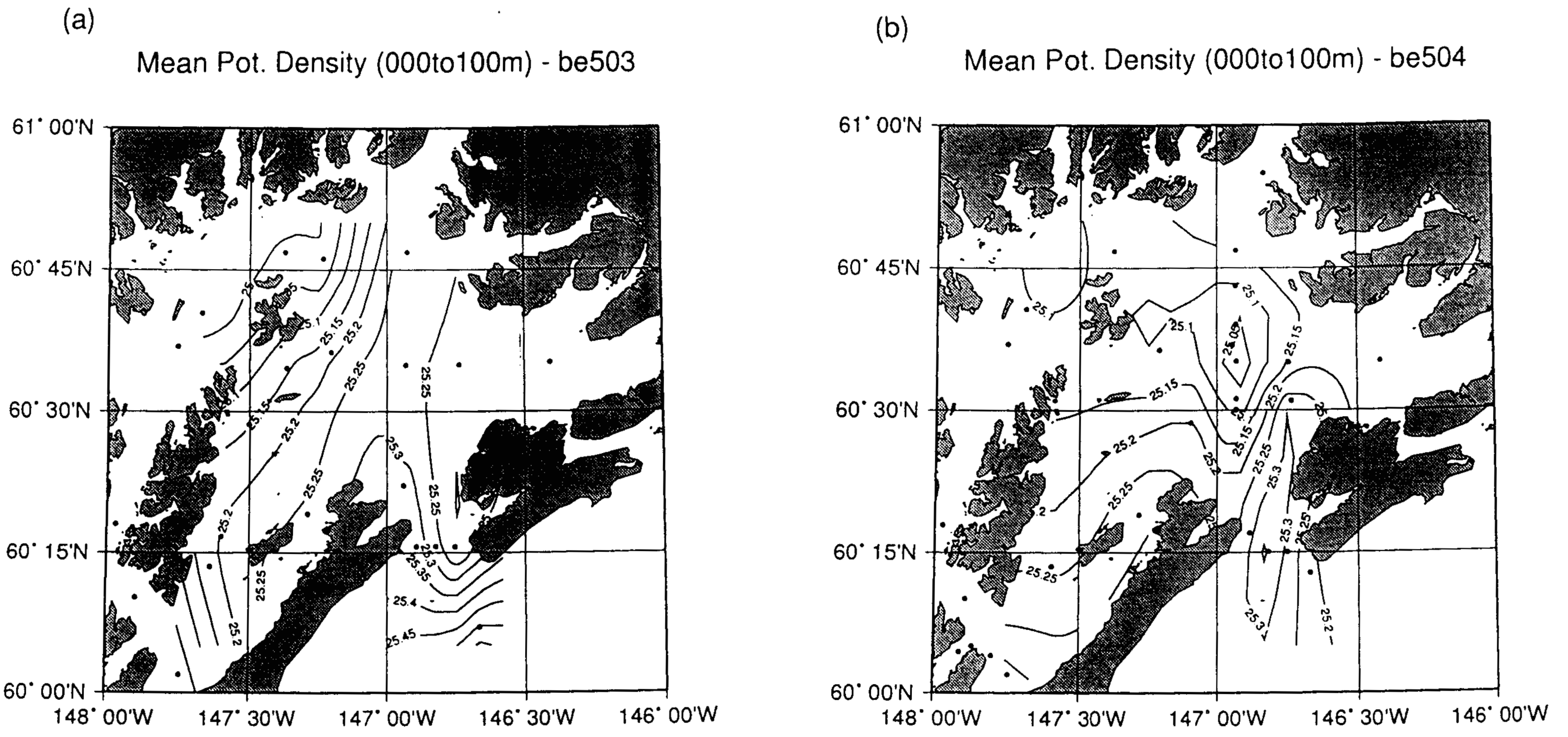
Mean Salinity (000to020m) - be505

Figure: 3


Mean Temperature (090to110m) - be509

Mean Salinity (090to110m) - be509

Figure: 4



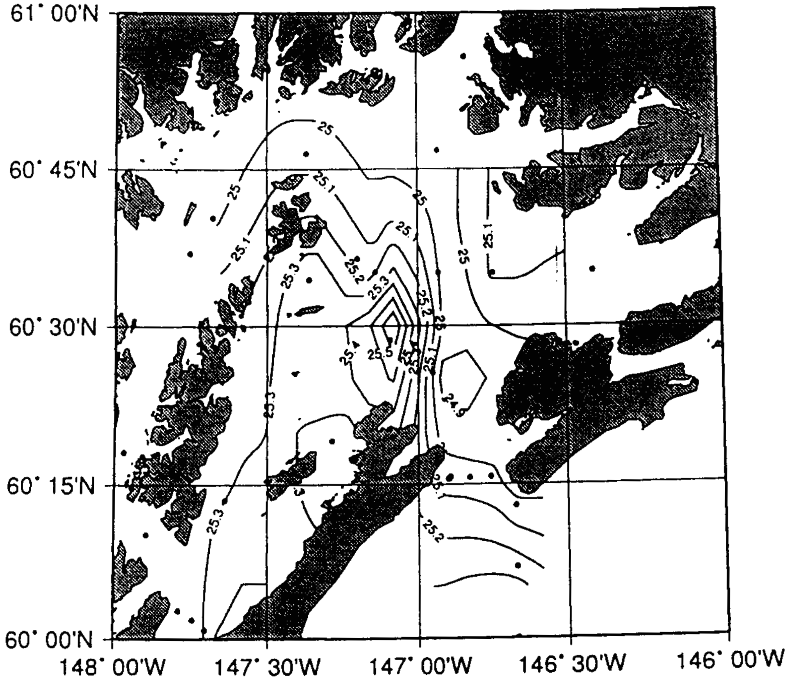
(a)

Mean Pot. Density (000to100m) - be503

(b)

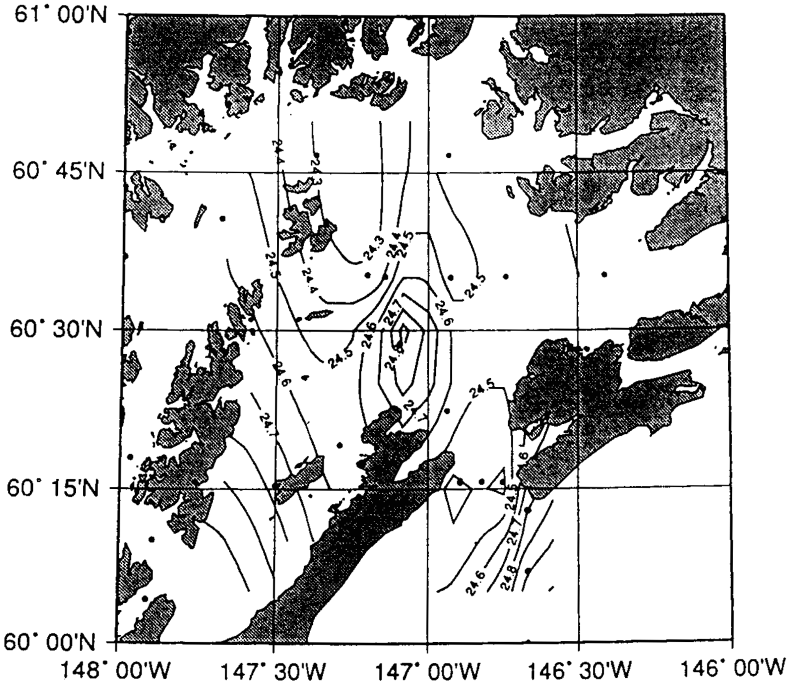
Mean Pot. Density (000to100m) - be504

(c)

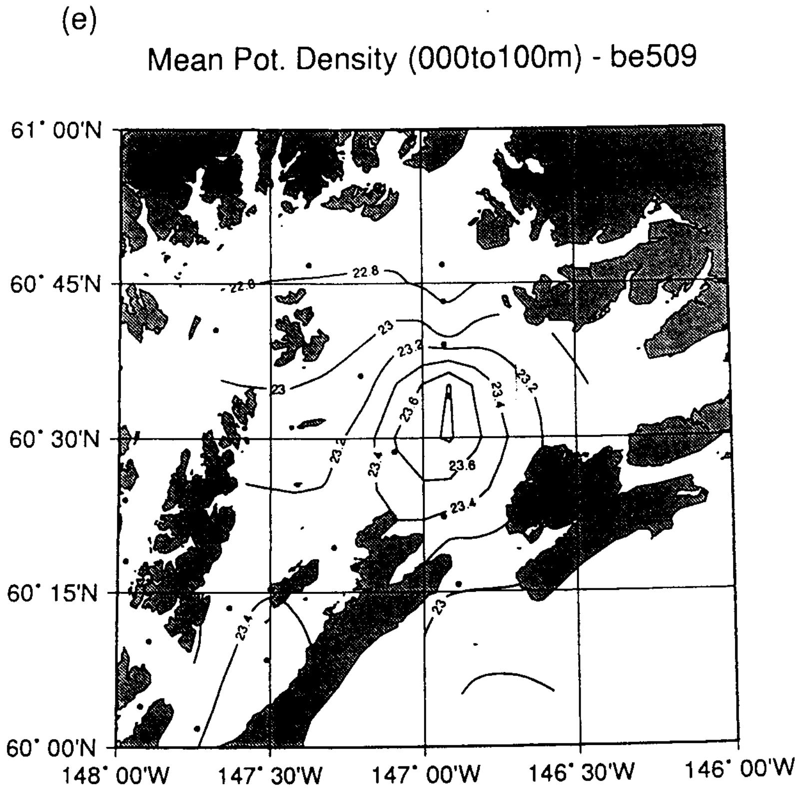


Mean Pot. Density (000to100m) - be505

(d)

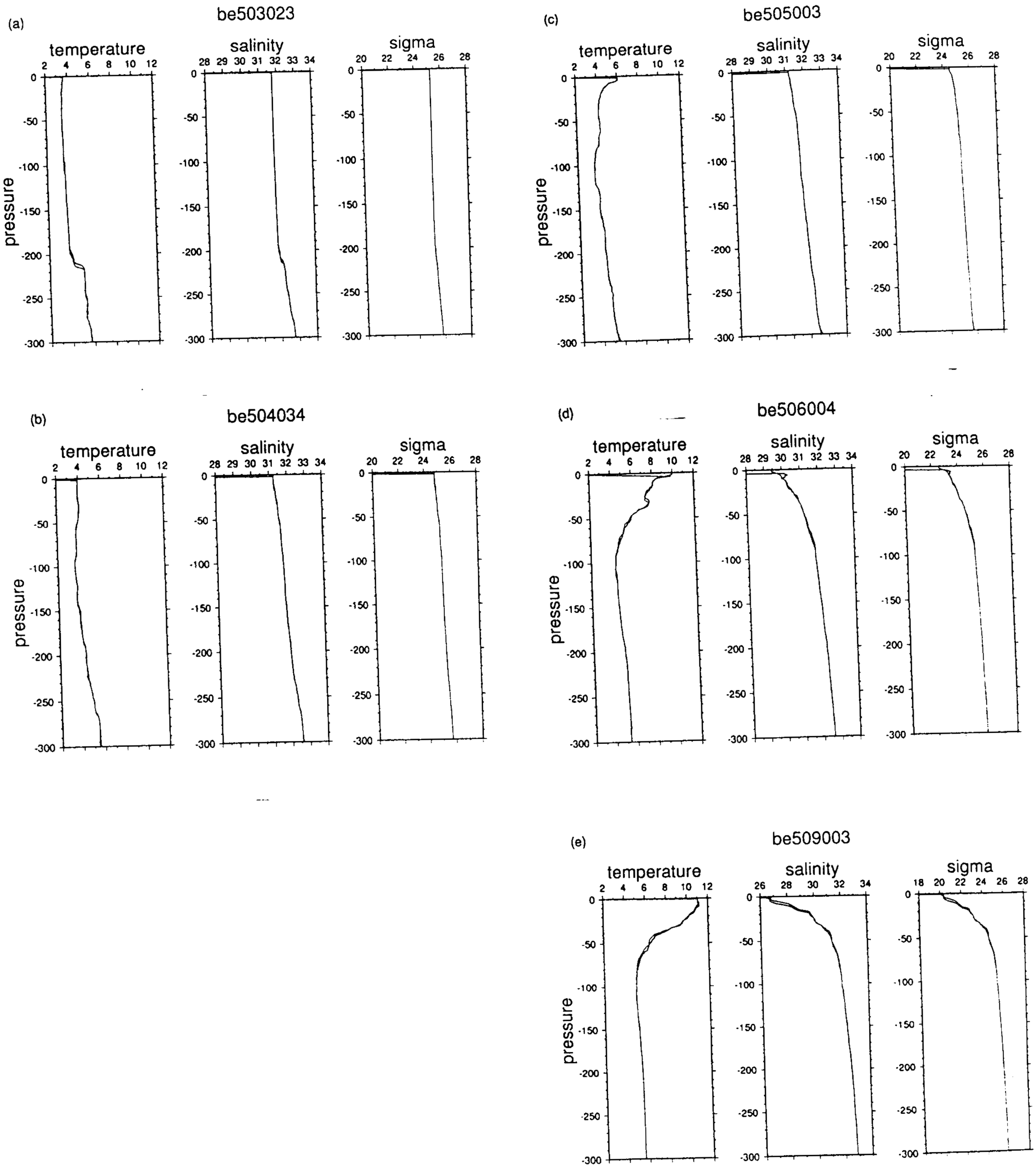


Mean Pot. Density (000to100m) - be506


(e)

Mean Pot. Density (000to100m) - be509

Figure: 5


(a) be503023

(b) be504034

(c) be505003

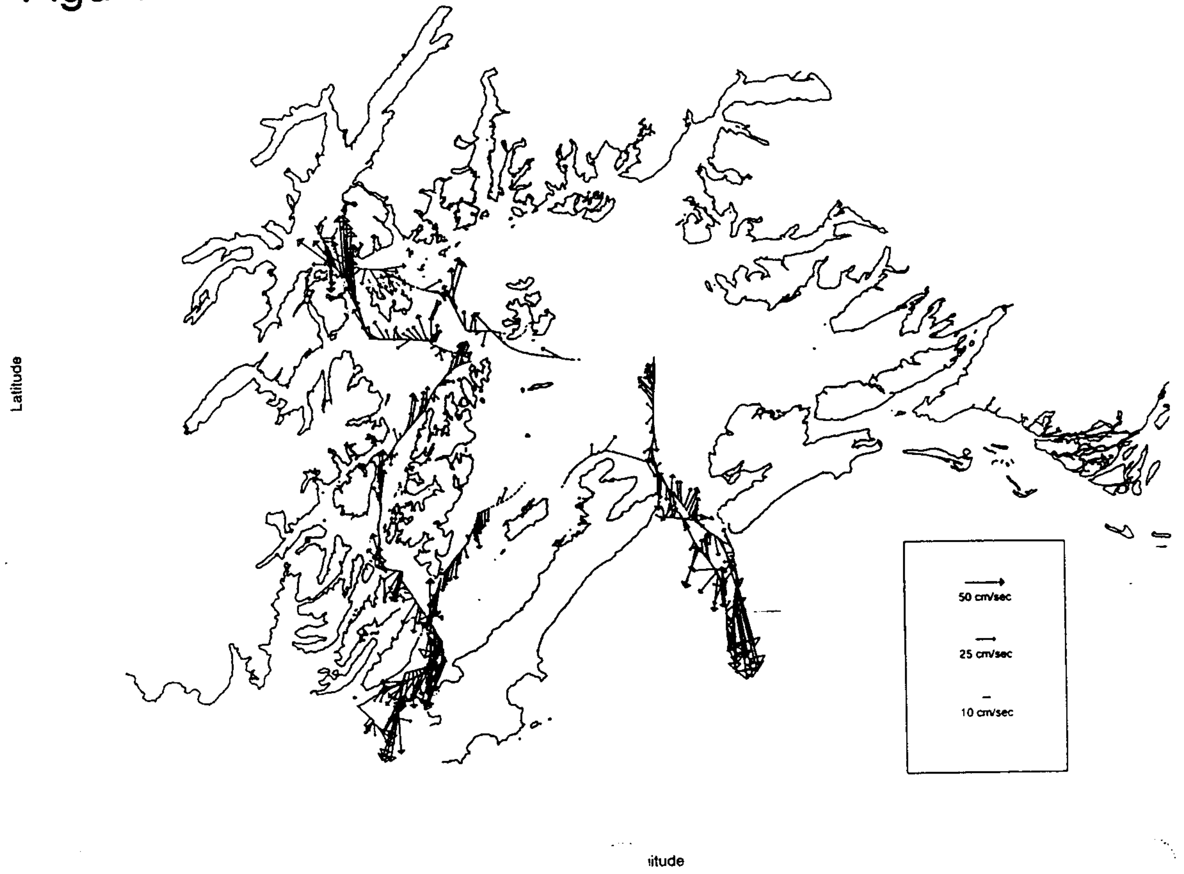
(d) be506004

(e) be509003

Figure: 6

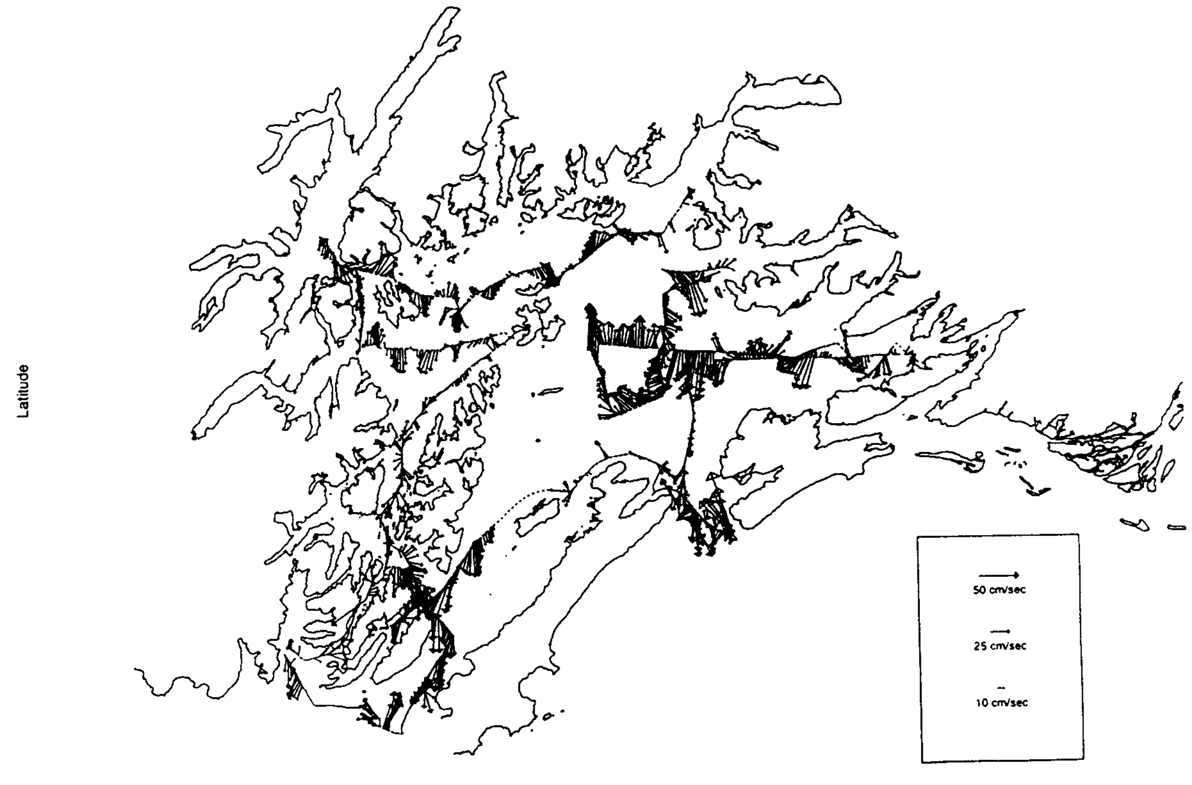
March 1995 ADCP Data
20/100 meters

(a)



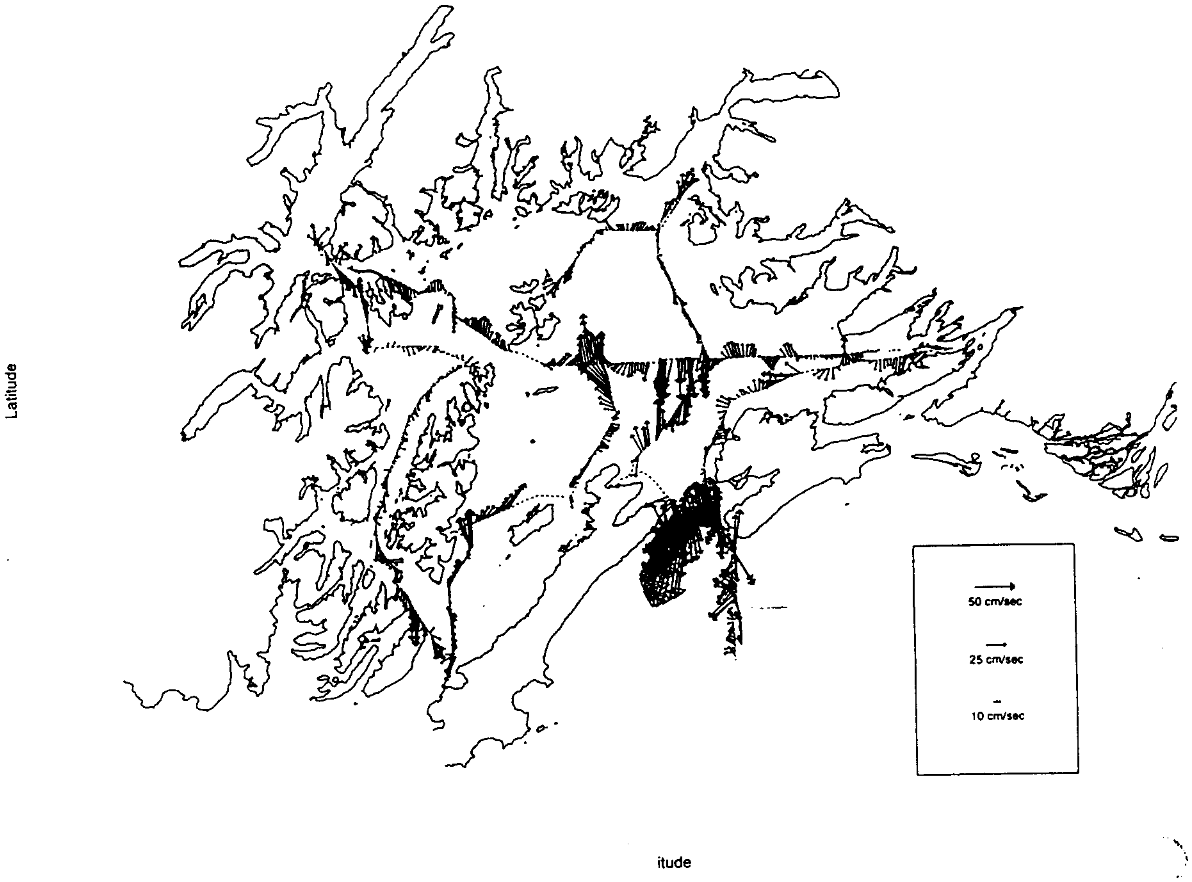
April 1995 ADCP Data
20/100 meters

(b)



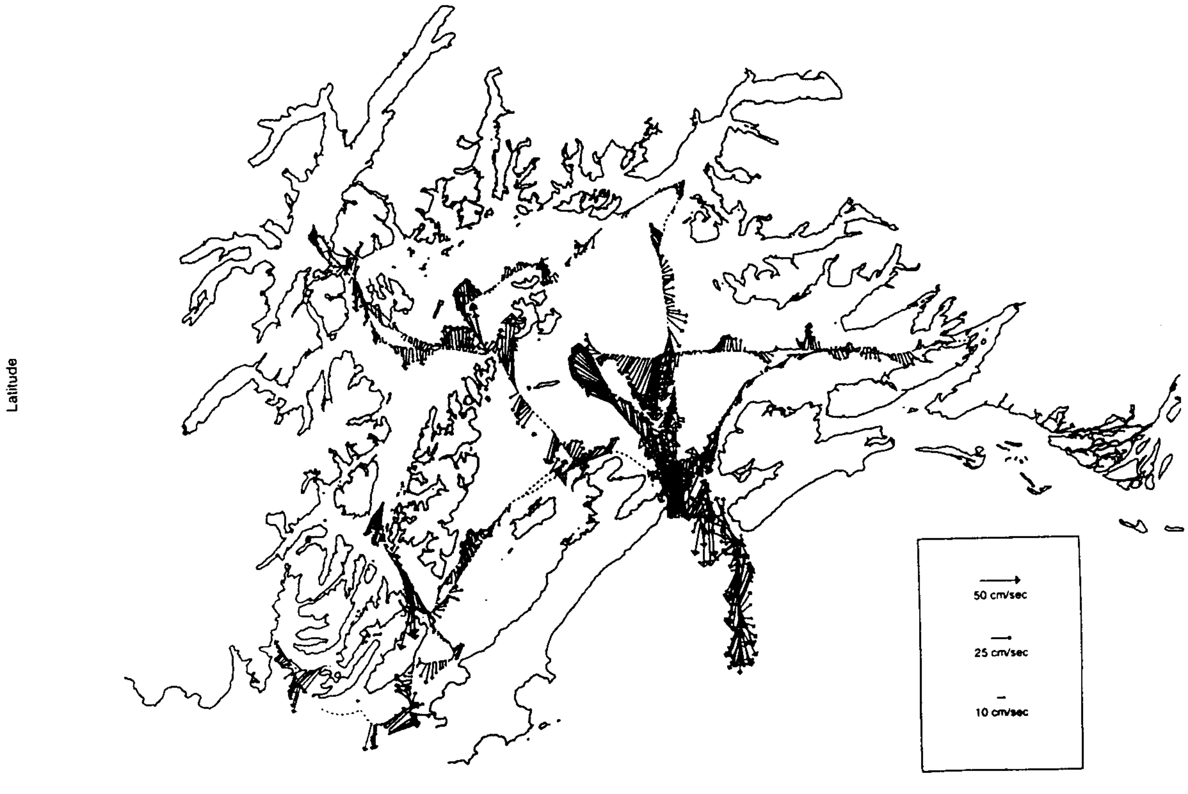
May 1995 ADCP Data
20/100 meters

(c)



June 1995 ADCP Data
20/100 meters

(d)



September 1995 ADCP Data
20/100 meters

(e)

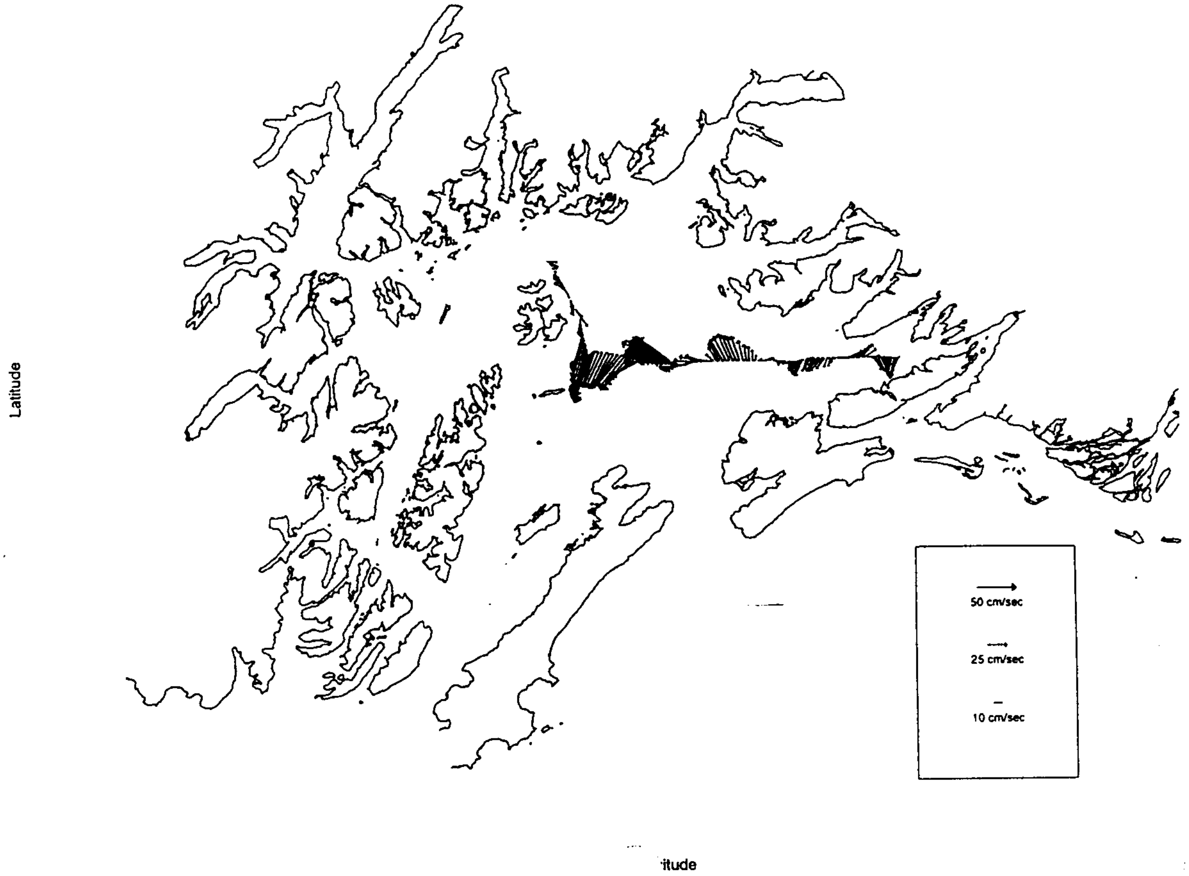
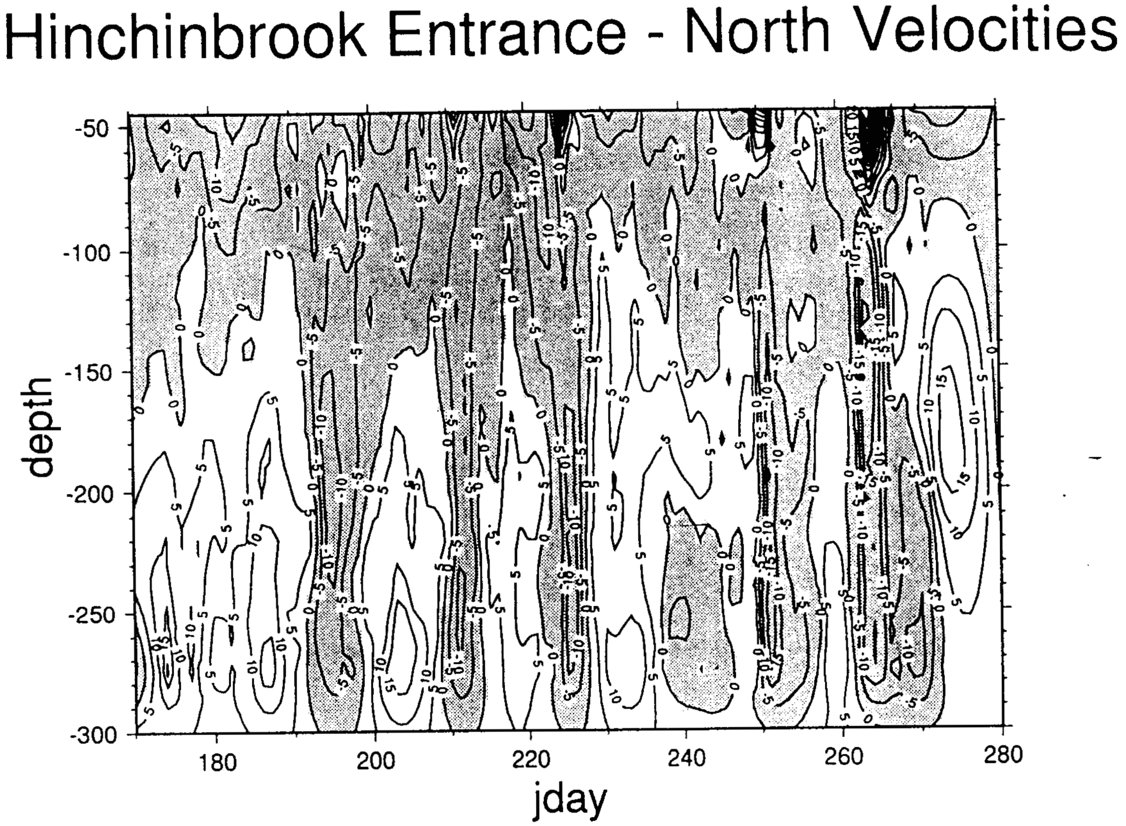


Figure: 7

(a)


Hinchinbrook Entrance - North Velocities

(b)

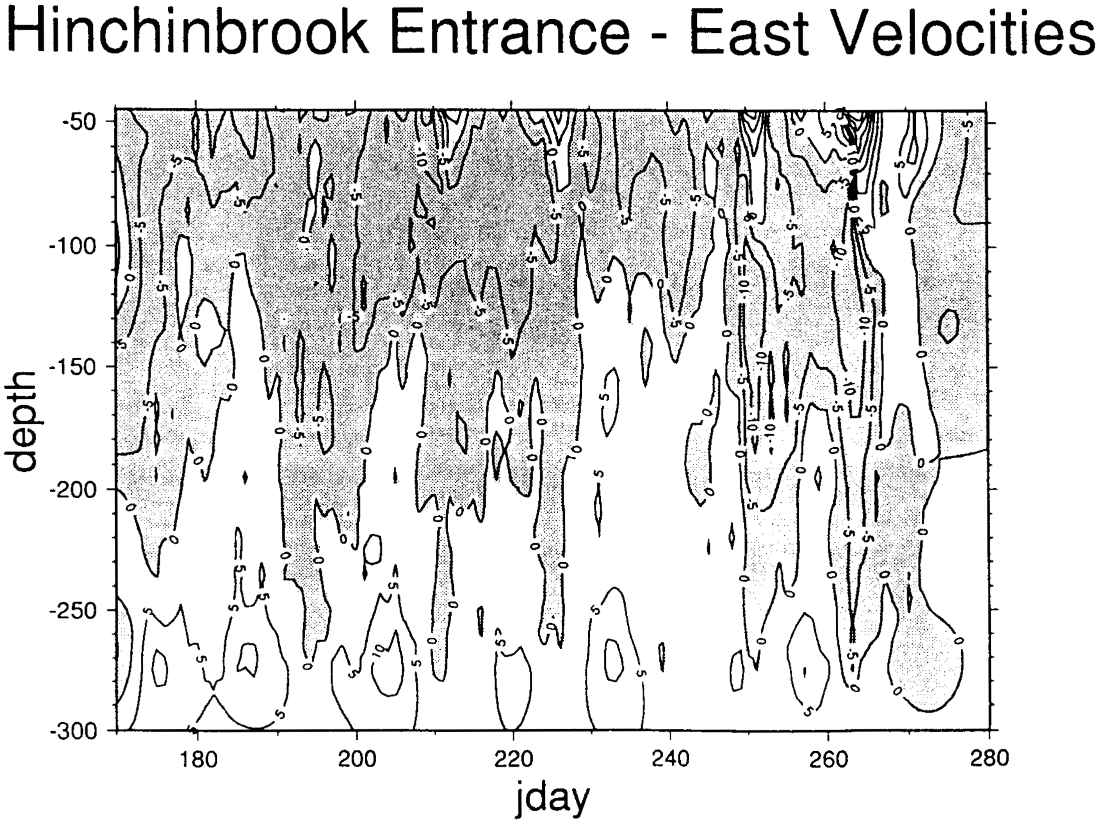
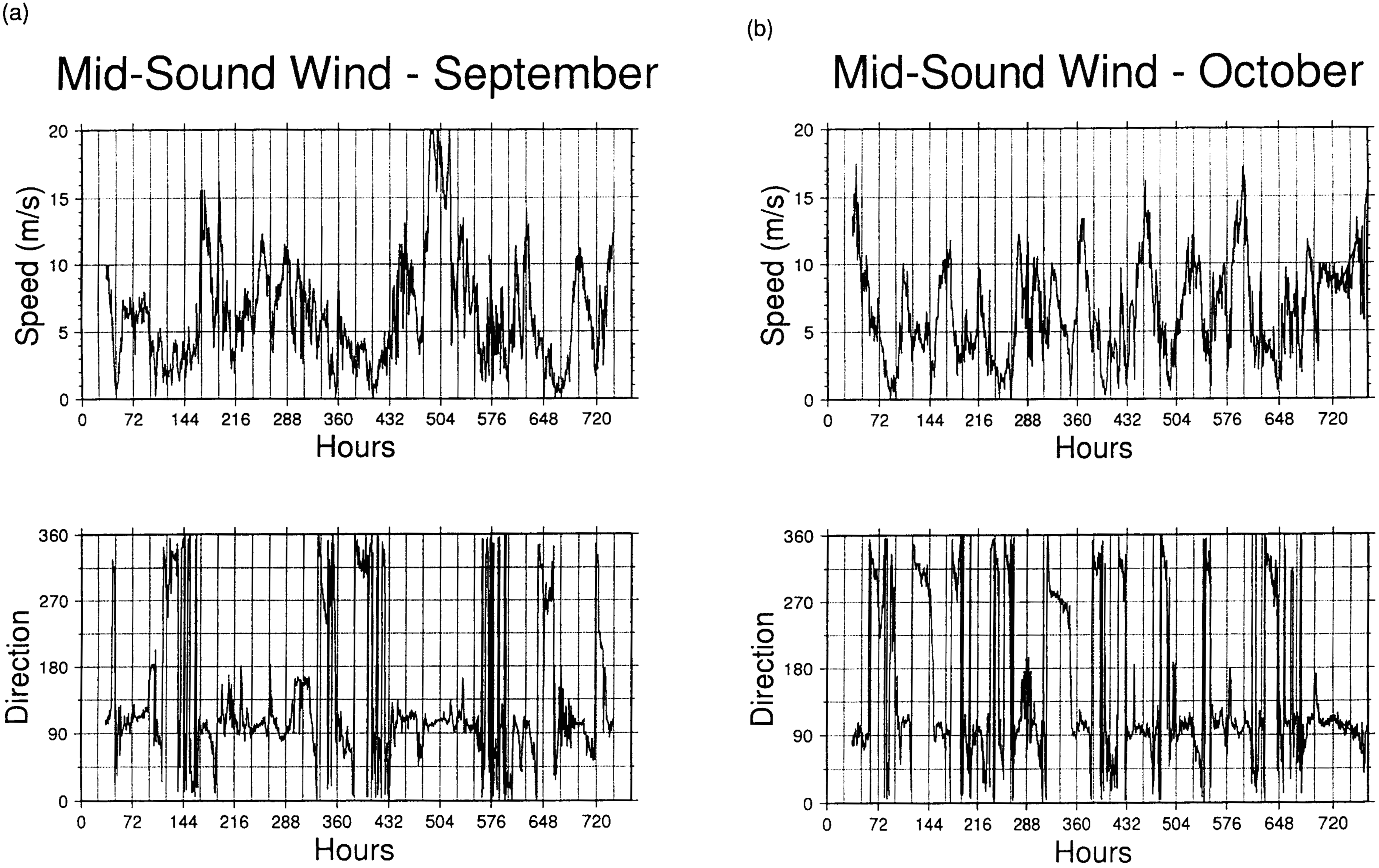

Hinchinbrook Entrance - East Velocities

Figure: 8

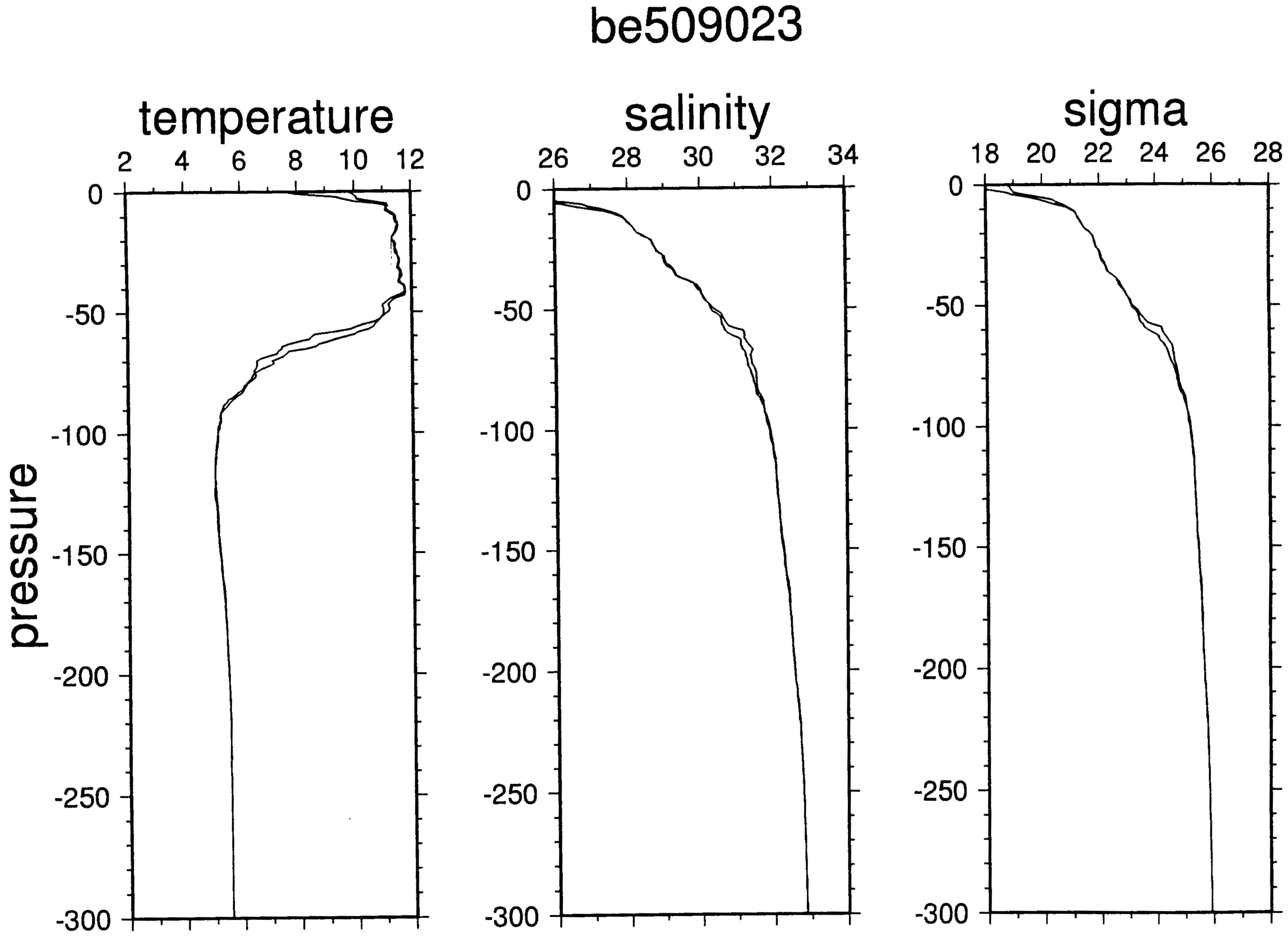

(a)

Mid-Sound Wind - September

(b)

Mid-Sound Wind - October

Figure: 9



be509023

temperature

salinity

sigma

Figure: 10

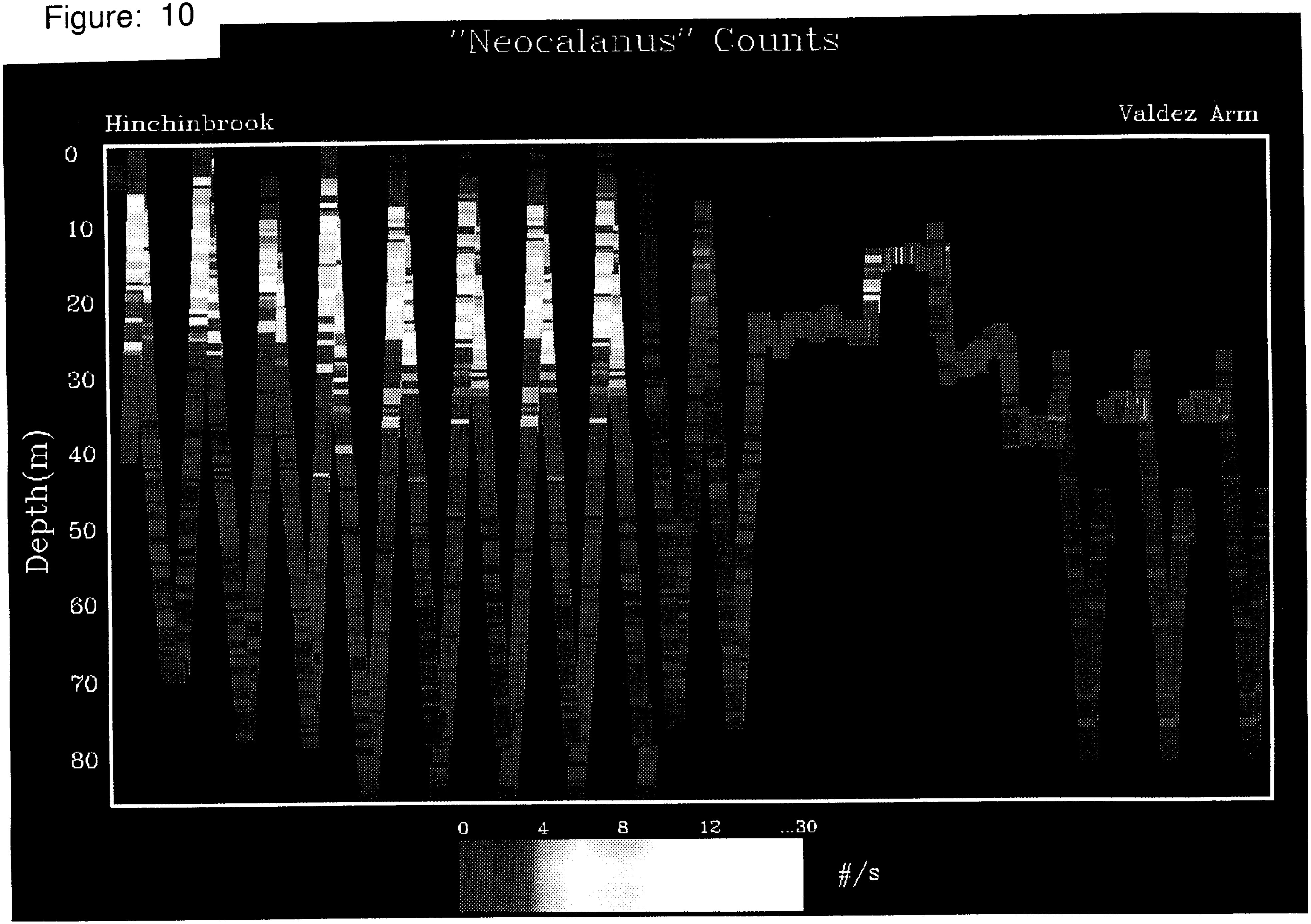
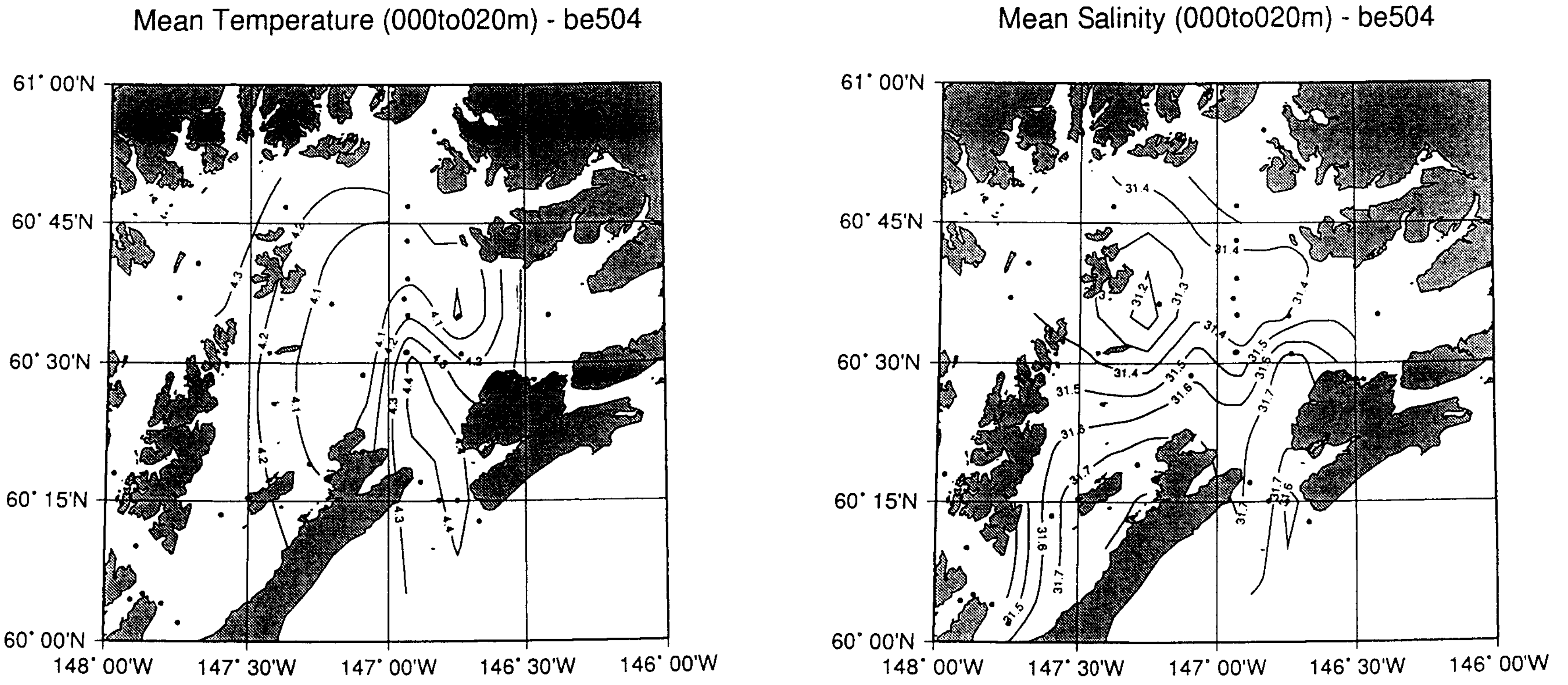

"Neocalanus" Counts
Hinchinbrook
Valdez Arm
Depth(m)
0
10
20
30
40
50
60
70
80
0
4
8
12
...30
#/s

Figure: 11


Mean Temperature (000to020m) - be504
Mean Salinity (000to020m) - be504
61° 00'N
60° 45'N
60° 30'N
60° 15'N
60° 00'N
148° 00'W
147° 30'W
147° 00'W
146° 30'W
146° 00'W
4.1
4.2
4.3
4.4
31.2
31.3
31.4
31.5
31.6
31.7
31.8