Geostrophic Current Analysis through the CenCal Box

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I. Introduction

A. California Current System

The California Current System is composed of numerous jets, filaments, eddies and three noteworthy currents. The California Current is the Eastern Boundary of the North Pacific Gyre. It is slow and broad compared to the Kuroshio Current on the Western Boundary of the Pacific Ocean. The California Current stretches from Washington, where it receives waters from the North Pacific Current, South, to the Baja Peninsula, where it turns to form the North Equatorial Current. The waters received from higher latitudes make the California Current cool and relatively fresh. Near the coast, however, the waters are more warm and saline due to the California Undercurrent. The California Undercurrent runs below and counter to the California Current, along the West Coast. Northwesterly summer winds force upwelling, which brings cooler, saltier waters directly adjacent to the Coast from greater depths. Southeasterly winter winds force downwelling, causing the California Undercurrent to rise to the surface and create the Davis Current, a poleward flowing, seasonal, surface current. Figure 1. is an infrared image depicting the California Current System's Sea Surface Temperature (SST).

B. Purpose

The purpose of this project is to qualitatively and quantitatively analyze geostrophic current velocities through the box bordered by the Central California Coast, and California Cooperative Oceanic Fisheries Investigations (CalCOFI) Lines 67, 70, and 77. It is to that end that seawater characteristics on the perimeter of the box will be examined, calculated geostrophic current velocities will be compared with measured ADCP velocities. Line by line geostrophic current velocities will be correlated to corresponding seawater characteristics and geostrophic volume transport will be considered.

II. Data Collection

A. Research Cruise

The Research Vessel Point Sur departed Moss Landing the morning of January 27, 2003 to collect a variety of meteorologic and oceanographic data within the Central California Coastal box (CenCal box). During the period from January 27 until February 3 (Leg 1), The R/V Point Sur moored two ADCPs, "N" and "S" and visited Stations 1-10 along CalCOFI Line 67, Stations 10-22 along CalCOFI Line 70 and Stations 22-30 along CalCOFI Line 77. With the exception of one deep cast, CTD data was collected at each station to a pressure of 1000dbar or max depth. This report will only concern itself with data collected from CTD and ADCP and only to a pressure level of 1000dbar or max depth. Figure 2. depicts the locations of stations visited over the course of Leg 1 and includes a comprehensive list of data collected on station and enroute.

B. Equipment

Sea-Bird Electronics 911plus CTD collected Continuous temperature, conductivity, and pressure data. Two Acoustic Doppler Current Profilers (ADCP) were used to measure current speeds along and across CalCOFI Lines 67, 70, and 77.

III. Data Manipulation

A. Equations

1. Geostrophic Velocity

Geostrophic velocities between adjacent stations were calculated using the temperature, salinity and pressure data collected at each CTD cast. Geostrophic flow is characterized by the balance between Coriolis Force and Pressure Gradient Force:

$$fv=-\alpha\nabla p$$

where f is the Coriolis Parameter (2 x Earth's speed of rotation (Ω) x the sine of latitude($\sin\varphi$)), v is parcel velocity, α is specific volume and p is pressure. Temperature and Salinity measurements were converted to specific volume using the Equation of State. Further algebraic manipulation and integration of the Pressure Gradient Force with respect to pressure yields the practical forms of the Geostrophic Equation:

$$V_g=(V_1-V_2)=\frac{\sum(\delta_B \times \Delta p)-\sum(\delta_A \times \Delta p)}{fL}$$

or

$$V_g=(V_1-V_2)=\frac{\Delta\Phi_B-\Delta\Phi_A}{fL}$$

where V_g is the geostrophic velocity between stations, V_1 is the velocity at depth, V_2 is the reference velocity at 1000m, δ is the specific volume anomaly, L is the horizontal difference between stations and Φ is the geopotential anomaly.

2. Volume Transport

Volume transport between stations was calculated by taking the double integral of velocity between stations and 2dbar pressure levels:

$$\iint V_g \, dxdz$$

or

$$\sum\sum V_g \, dxdz$$

B. Data Processing

Geostrophic current velocities between stations at 2dbar intervals were calculated using CTD data, which had already been processed to include the geopotential anomaly and geographic coordinates station. This data was loaded into a MATLAB program which, in addition to the current velocities already mentioned, calculated the distance between adjacent stations and the cumulative distance from Moss Landing to Station 30.

Depth and geopotential anomaly data was then entered into Microsoft Excel with the calculated distances between adjacent stations to recalculate geostrophic current velocities between stations as a means of checking previous calculations. Differences between MATLAB and Excel calculations were negligible and likely due to human error. MATLAB calculated geostrophic current velocities between stations were entered into Excel and used to calculate geostrophic volume transport through the CenCal box.

C. Plotting

Cumulative distances, measurement depths, and their associated velocities calculated by MATLAB were loaded into Surfer 8 for plotting. MATLAB was also used create plots of Temperature vs. Salinity.

IV. Analysis

A. Sea Water Characteristics

1. Temperature

Temperature, particularly at relatively shallow depths, is one of the most important seawater characteristics. This is due, in part, to the relative ease with which it can be measured, but, more important, because of its use as a parameter in determining other seawater characteristics and its effect on dynamic processes. Figure 3 represents the 1000m temperature profile in ^{o}C from Moss Landing, around the CalCOFI Lines, to Port St. Louis. Significant coastal upwelling can be discerned on either side of the plot from the Surface to 200m. Warm surface waters can be attributed to eddies or, possibly near the shore, the Davis current. Another feature to note is the deep upwelling situated roughly at the corners of the box, Stations 10 and 22.

2. Salinity

Salinity is another important parameter in the determination of circulation. Figure 4 represents the 1000m salinity profile from Moss Landing, around the CalCOFI Lines, to Port St. Louis. There is clearly upwelling of salty, deep waters on the coast from 200m to the surface, corresponding to the upwelling discerned on the temperature plot. Unlike temperature, however, there seems to be a salinity depression in the vicinity of stations 10 and 22 and salty upwelling along the CalCOFI Lines.

3. Temperature and Salinity

Line by Line temperature data plotted against salinity (Figure 5, next page) further highlights the differences in measurements taken at stations closer and farther from shore. Most notable are the differences along Line 67, where deep measurements taken and Stations 9 and 10 are conspicuously colder and fresher than measurements taken at the 8 stations closer to shore. This separation seems to persist throughout the

CTD cast, into shallower waters. Stations along line 70 are fairly uniform in distance from the shore. Interestingly, there is a relatively wide spread near the surface between Station 19 and, almost adjacent, Station 22. Line 77 is homogeneous compared to the previously mentioned Lines.

4. Density

In terms of geostrophic flow, density, especially its horizontal gradient, is the characteristic of greatest interest. It is with this horizontal density gradient that the direction of geostrophic flow will be checked. Figure 6 represents the 1000m density anomaly profile in kg/m^3 from Moss Landing, around the CalCOFI Lines, to Port St. Louis. Much of the density anomaly profile mirrors the previously examined temperature and salinity profiles. Coastal density values, compared along the same pressure level, go from being lighter at 250dbar to heavier at the surface. The lightest water is at the surface, between stations 9 and 13, corresponding to the warm, fresh water identified earlier.

B. Comparison of Calculated Geostrophic Current Velocity With ADCP Measured Currents

1. Similarities

Some striking similarities exist between the calculated geostrophic flow out of the box and the flow measured by the ADCP. Figure 7 is a plot of ADCP Measured current out of the box from 0-300m. Figure 8 is a plot of calculated geostrophic current velocity. For both figures, blue shaded, negative contours represent flow into the box while green shaded, positive contours are outflow in cm/s. White areas are areas of no flow. Significant inflow side by side with significant outflow was both calculated and measured from roughly 50 to 150km from Moss Landing. Surface inflow at 175km and 540km from Moss Landing, and outflow at 275km and 400km from Moss Landing are also attributes common to both plots.

2. Differences

Fewer but no less significant differences also exist between the calculated geostrophic flow out of the box and the flow measured by the ADCP. The most striking difference is the ADCP inflow at 475km from 0-300m. There is some outflow at roughly the same distance from Moss Landing on the geostrophic current velocity plot, but it's not nearly as strong or deep. The geostrophic plot depicts inflow at 325km distance at 10cm/s. The ADCP plot depicts a strong surface inflow at 375km from Moss Landing. Other differences exist, but are on the order of 5cm/s not worthy of note.

C. Seawater Characteristic Correlation

1. CalCOFI Line 67

Figure 9 shows plots of temperature, salinity, density anomaly, and geostrophic flow out of Line 67 from 0-1000m. The deep upwelling of cold water at the corners and depression of fresh water at the same corners noted earlier tend to level the deep isopycnals, creating slower currents below 400m. Taking a closer look at the upper 300meters (Figure 10), however, strong gradients in temperature, salinity, and density and their effect on current are easily identifiable. Depressions of warm, fresh, "light" water 50-100km and 140-165km from Moss Landing produce strong, alternating in and out flow. Though not the strongest current, poleward outflow, flanking the coast, is consistent with the negative horizontal density gradient and the Davis Current.

2. CalCOFI Line 70

Figure 11 shows plots of temperature, salinity, density anomaly, and geostrophic flow out of Line 70 from 0-1000m. As in Line 67, isotherms, turning up at the edges, juxtaposed with salinity isopleths, turning down, create straight, level isopycnals in deeper waters. In the upper 300meters (Figure 12), temperature, salinity and density contours fluctuate frequently under 50m. Each contour wave has a steep slope, however, the amplitude is small, so there isn't a strong enough gradient to produce a substantial current. Above 50 m, there is a more sizeable gradient at approximately 325km from Moss Landing, which corresponds to strong inflow at the same distance. The strongest flow across Line 70, though, is at 250km distance, where the gradient appears to be weakest. Interestingly, the ADCP plot (Figure 7) also demonstrates fairly strong outflow at 250km.

3. <u>CalCOFI Line 77</u>

Figure 13 shows plots of temperature, salinity, density anomaly, and geostrophic flow out of Line 77 from 0-1000m. As in the previous two Line analyses, opposing temperature and salinity isopleths level out isopycnals in waters deeper than 400m. Geostrophic currents are understandably weak in this area. In the upper 300meters (Figure 14), outflow at 400km distance from Moss Landing corresponds to the negative density gradient between Stations 20 and 22 on Line 70 (Figure 12). At 500km distance surface outflow does not relate to any negatively oriented isopycnals. Near Port San Louis, poleward inflow is consistent with the density gradient, possibly the Davis Current.

D. Volume Transport

Volume transport calculations, summarized in Tables 1, 2, and 3, generated a net transport of 5.44Sv out of the box.

Line 67 Volume Tranport

Station #	Sum V m/s	dZ, m	dX, m	Vol. Out m^3/s	Vol. Out (Sv)
1-2	13.3041039	26.60821	16655	443159.7009	0.443159701
2-3	15.9459796	31.89196	19597.8	625012.238	0.625012238
3-4	-47.3035604	-94.6071	18813.5	-1779891.067	-1.779891067
4-5	28.789281	57.57856	18800	1082476.966	1.082476966
5-6	-14.8385893	-29.6772	17697.2	-525202.9651	-0.525202965
6-7	-27.206984	-54.414	18654.4	-1015059.925	-1.015059925
7-8	30.3180243	60.63605	18617.4	1128885.571	1.128885571
8-9	25.9284783	51.85696	18240.2	945881.2598	0.94588126
9-10	12.8627771	25.72555	18524	476540.166	0.476540166
Total Line 67 Volume Out (Sv) =					**1.381801945**

Table 1

Line 70 Volume Tranport

Station #	Sum V m/s	dZ, m	dX, m	Vol. Out m^3/s	Vol. Out (Sv)
10-11	-17.2557199	-34.5114	18727.5	-646312.9889	-0.646312989
11-12	18.2815128	36.56303	18335.8	670412.3248	0.670412325
12-13	10.3732161	20.74643	18577.9	385425.1428	0.385425143
13-14	-1.9886179	-3.97724	18768.5	-74646.75011	-0.07464675
14-15	4.7917977	9.583595	18590	178159.0385	0.178159038
15-16	17.7459707	35.49194	18704.3	663851.9195	0.66385192
16-17	-1.5725942	-3.14519	18507.5	-58209.57431	-0.058209574
17-18	8.4294819	16.85896	18375.3	309788.5175	0.309788518
18-19	-28.3226999	-56.6454	18943.4	-1073056.467	-1.073056467
19-20	7.615009	15.23002	18394	280140.9511	0.280140951
20-21	27.6667112	55.33342	18642.4	1031547.794	1.031547794
21-22	8.5743523	17.1487	18552.3	318147.9124	0.318147912
Total Line 70 Volume Out (Sv) =					**1.98524782**

Table 2

Line 77 Volume Tranport

Station #	Sum V m/s	x dZ, m	x dX, m	Vol. Out m^3/s	Vol. Out (Sv)
21-22	14.315112	28.63022	18258.7	522750.6709	0.522750671
23-24	7.6565279	15.31306	18834.5	288413.7495	0.288413749
24-25	22.9832353	45.96647	18160.8	834787.8793	0.834787879
25-26	-3.5925103	-7.18502	18384.8	-132095.1667	-0.132095167
26-27	2.8132163	5.626433	18468.2	103910.0825	0.103910083
27-28	10.2204715	20.44094	18340.2	374890.9828	0.374890983
28-29	3.4838034	6.967607	18488.4	128819.9016	0.128819902
29-30	-1.3986442	-2.79729	18559.2	-51915.43487	-0.051915435
Total Line 77 Volume Out (Sv) =					**2.069562665**

Total Volume Transport Out of the Box (Sv) =	**5.43661243**

Table 3

V. Conclusion

Examination of seawater characteristics along the perimeter of the CenCal box and the impact those characteristics have on circulation, demonstrate the complexity of the California Current System. Despite this complexity, calculated geostrophic current velocities proved comparable to measured ADCP velocities. There was some disagreement between the two, but these differences were of a much smaller magnitude to the points of harmony. Line by line, geostrophic current velocities coupled nicely with seawater characteristics at the same general location. Like the ADCP comparison, there were occasions of conflict, however, again, like the ADCP comparison, moments of discord were minor compared with the overall harmony. Geostrophic volume transport, on the other hand was considerably higher than expected. This is probably due to high winds creating Ekman convergence and/or inward flow from coastal upwelling below the 1000m maximum shared depth.

VI. Acknowledgement

Thanks to Doctor Collins and Tarry Rago for the 11th hour assist.

VI. References

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Pond, S., and G.L. Pickard, 1983. *Introductory Dynamical Oceanography*, 2nd Ed., pp 68-77, Butterworth/Heinemann.

Rago, T., assemble_ArcRaster.m

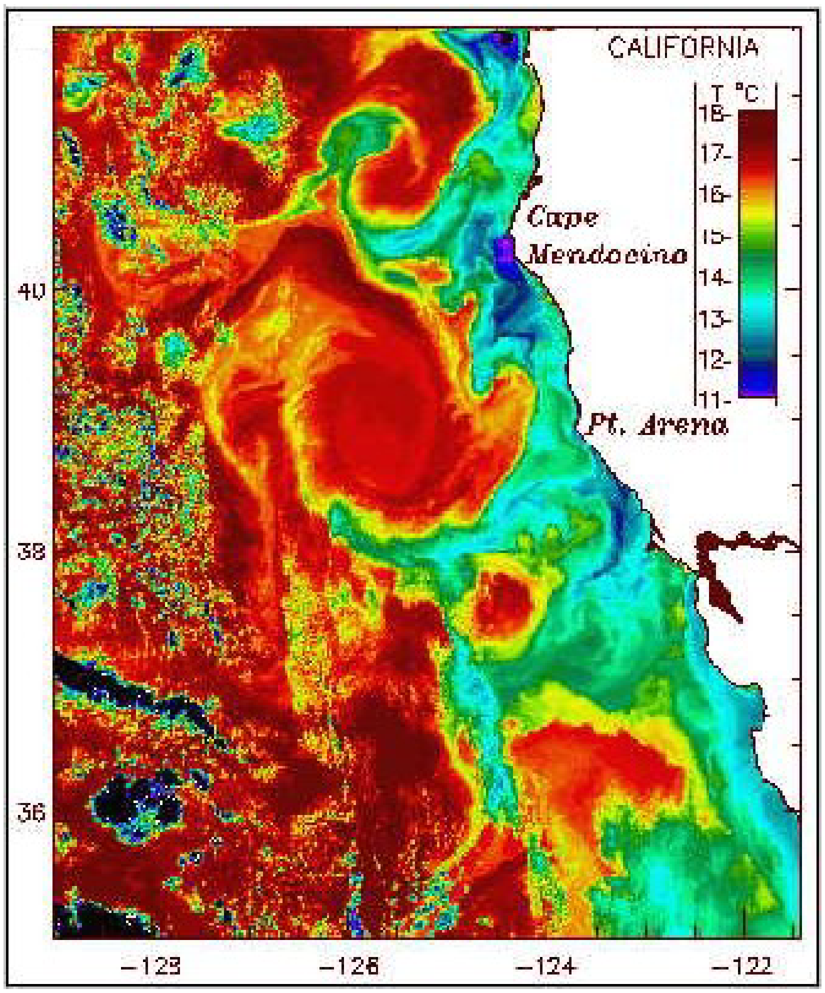

CALIFORNIA
T °C
18-
17-
16-
15-
14-
13-
12-
11-
Cape
Mendocino
Pt. Arena
40
38
36
−128
−126
−124
−122

Figure 1.

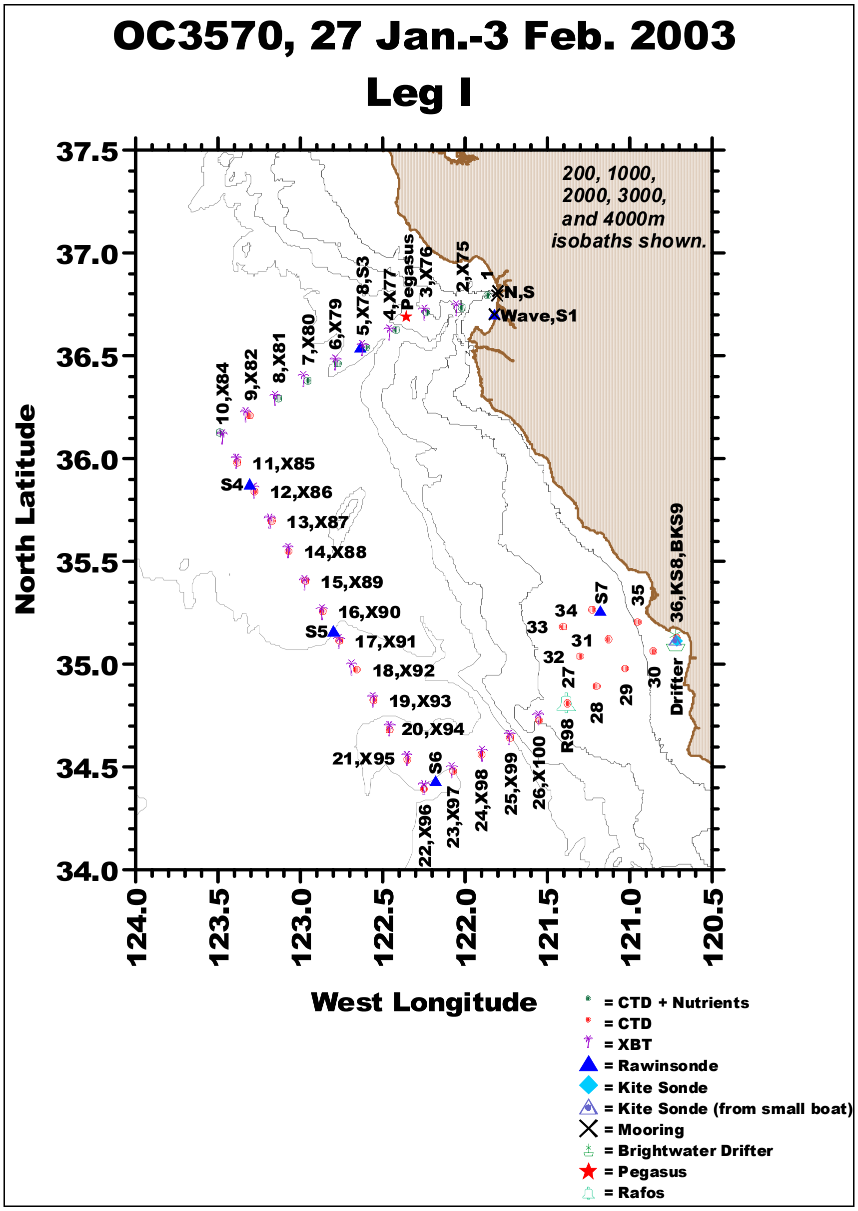

OC3570, 27 Jan.-3 Feb. 2003
Leg I
200, 1000, 2000, 3000, and 4000m isobaths shown.
North Latitude
West Longitude
37.5
37.0
36.5
36.0
35.5
35.0
34.5
34.0
124.0
123.5
123.0
122.5
122.0
121.5
121.0
120.5
1
N,S
Wave,S1
2,X75
3,X76
Pegasus
4,X77
5,X78,S3
6,X79
7,X80
8,X81
9,X82
10,X84
11,X85
S4
12,X86
13,X87
14,X88
15,X89
16,X90
S5
17,X91
18,X92
19,X93
20,X94
21,X95
S6
22,X96
23,X97
24,X98
25,X99
26,X100
R98
27
28
29
30
31
32
33
34
S7
35
36,KS8,BKS9
Drifter
= CTD + Nutrients
= CTD
= XBT
= Rawinsonde
= Kite Sonde
= Kite Sonde (from small boat)
= Mooring
= Brightwater Drifter
= Pegasus
= Rafos

Figure 2

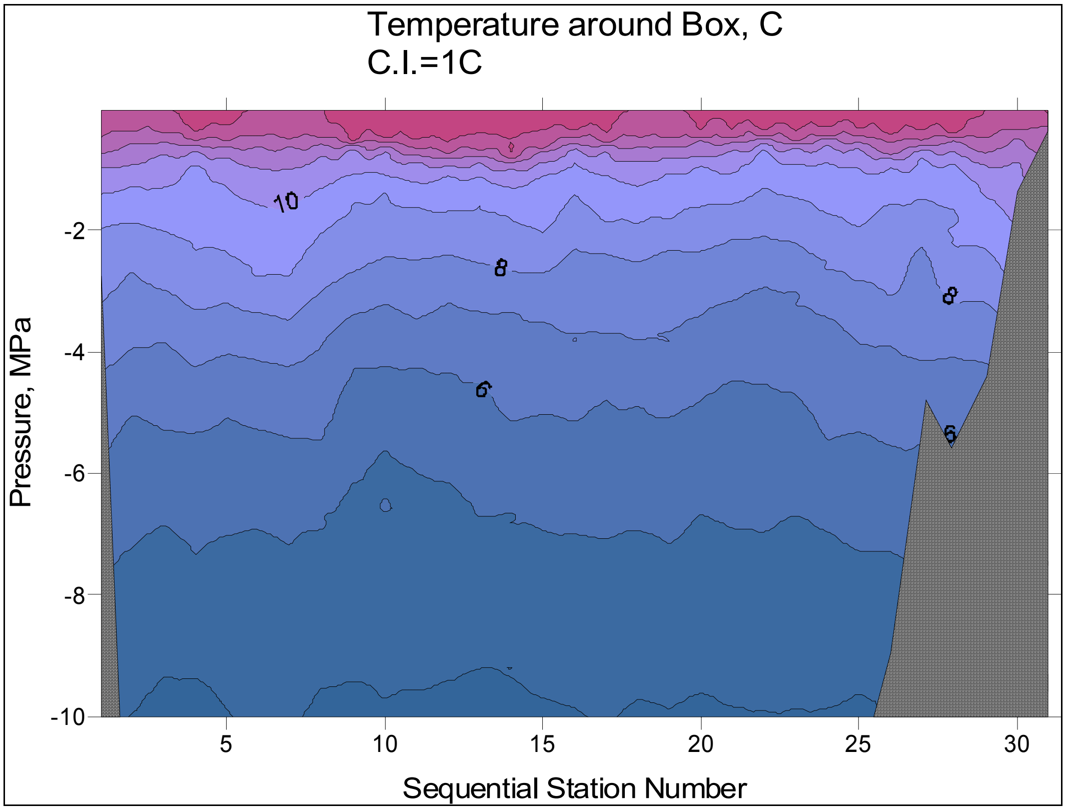


Figure 3

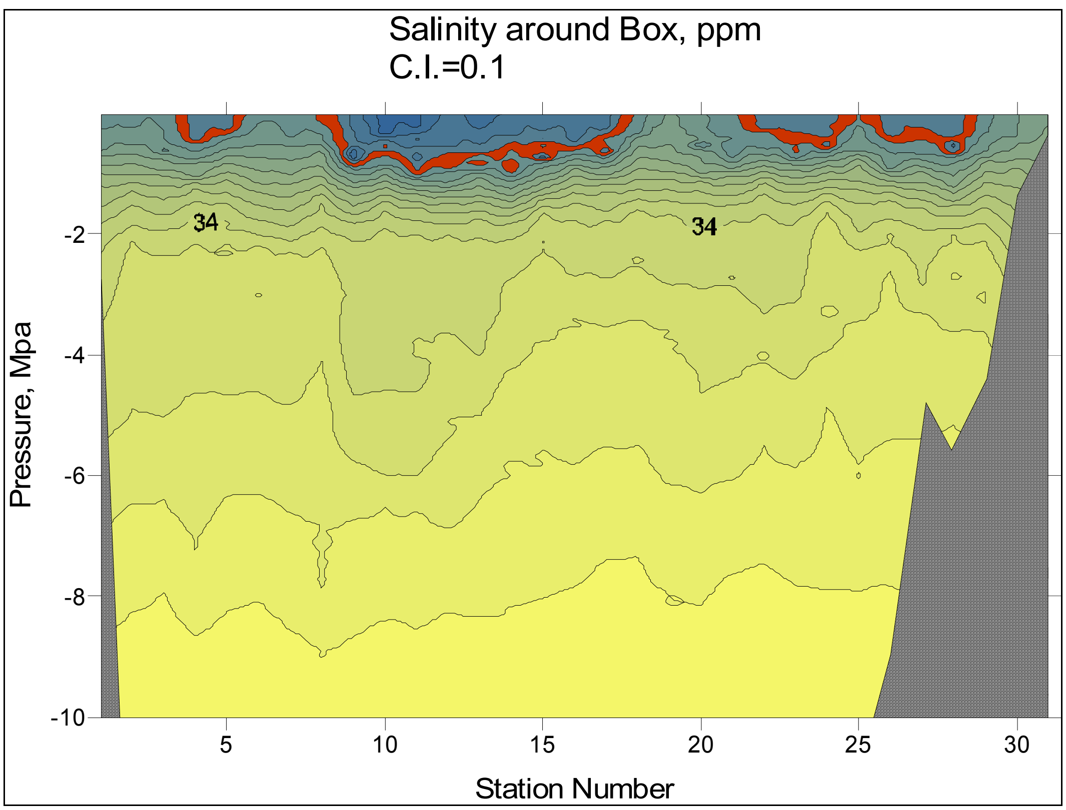
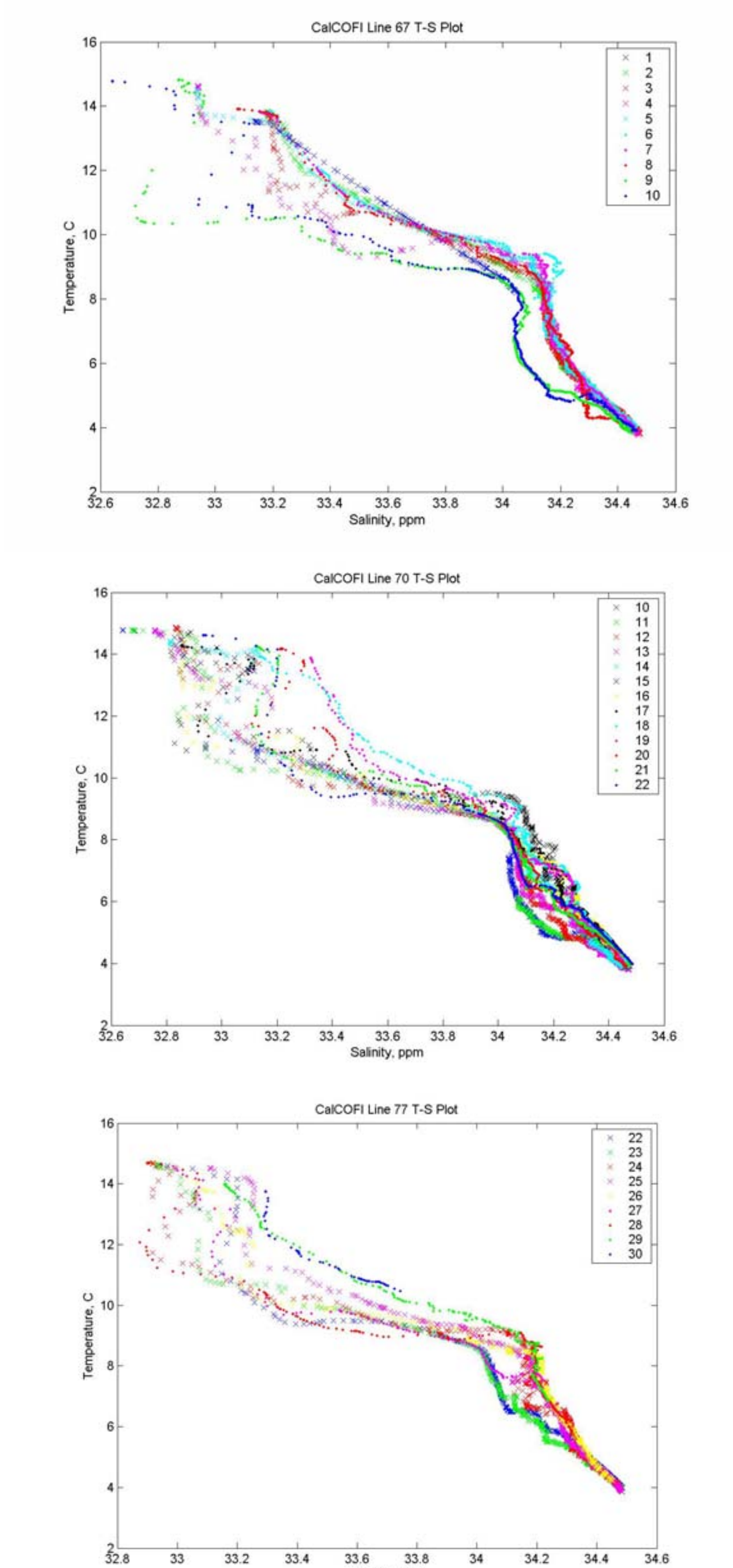
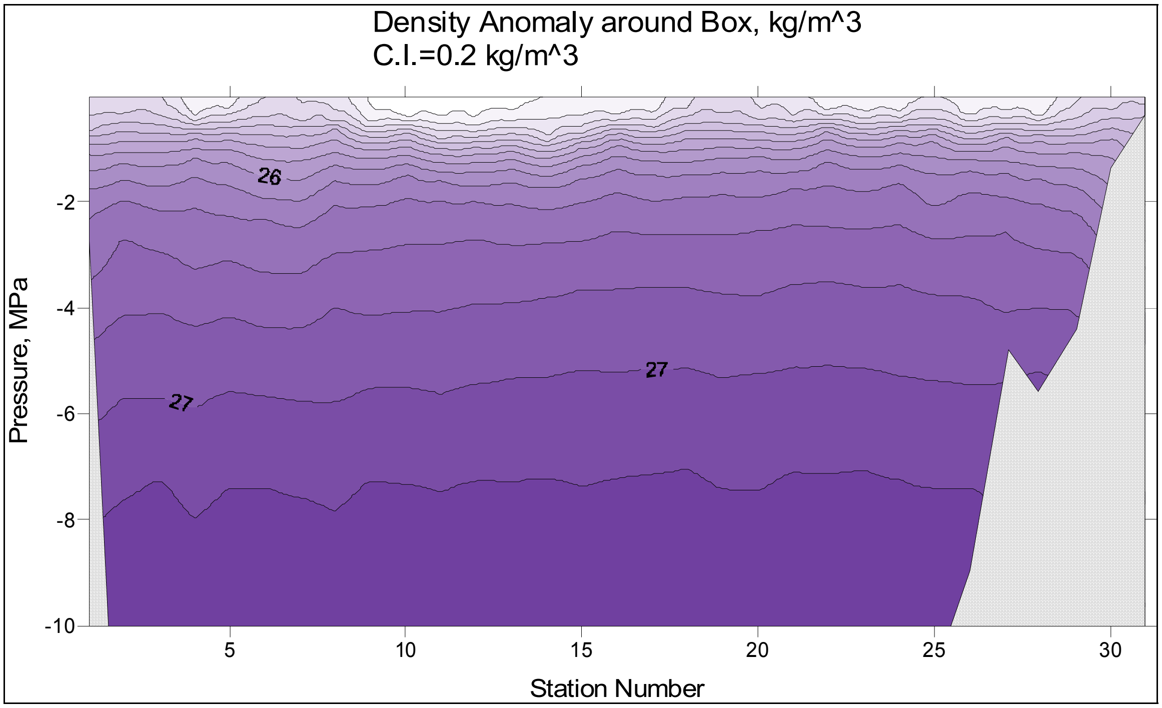


Figure 4



CalCOFI Line 67 T-S Plot
Temperature, C
Salinity, ppm
16
14
12
10
8
6
4
2
32.6
32.8
33
33.2
33.4
33.6
33.8
34
34.2
34.4
34.6
1
2
3
4
5
6
7
8
9
10
CalCOFI Line 70 T-S Plot
Temperature, C
Salinity, ppm
10
11
12
13
14
15
16
17
18
19
20
21
22
CalCOFI Line 77 T-S Plot
Temperature, C
Salinity, ppm
22
23
24
25
26
27
28
29
30

Figure 5



Density Anomaly around Box, kg/m^3
C.I.=0.2 kg/m^3
26
27
27
Pressure, MPa
-2
-4
-6
-8
-10
5
10
15
20
25
30
Station Number

Figure 6

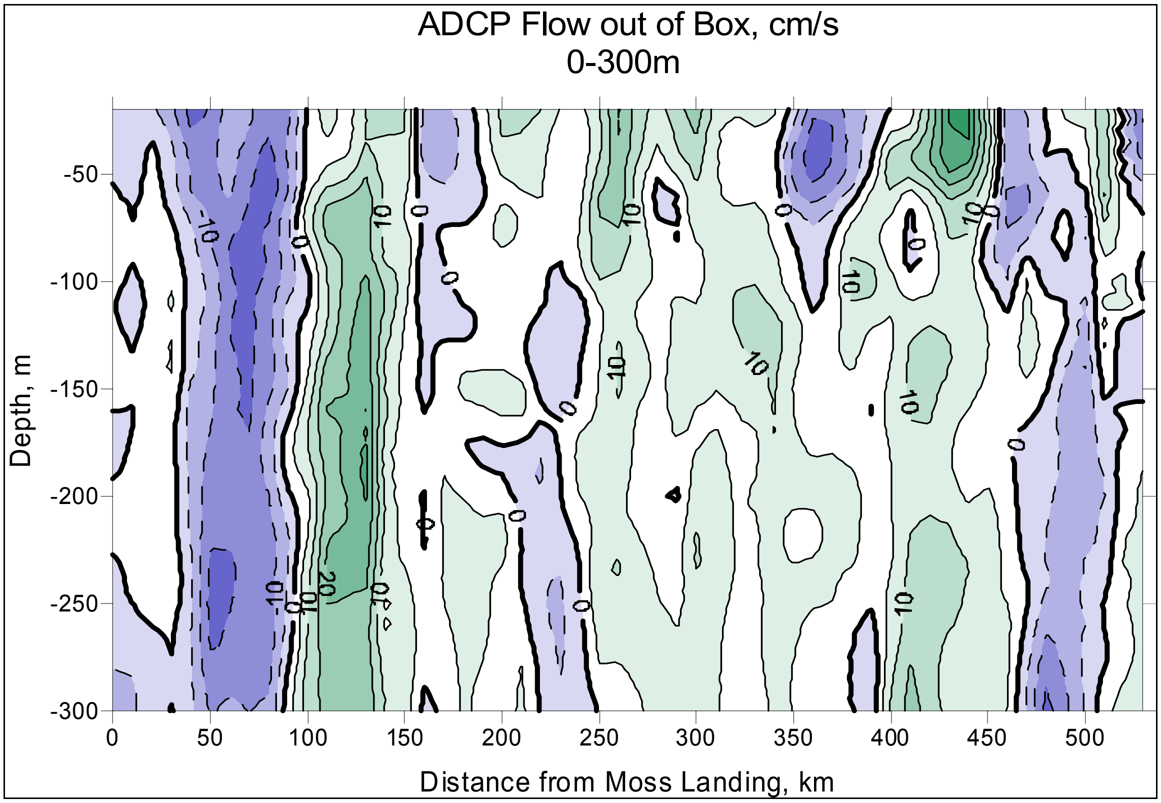


Figure 7

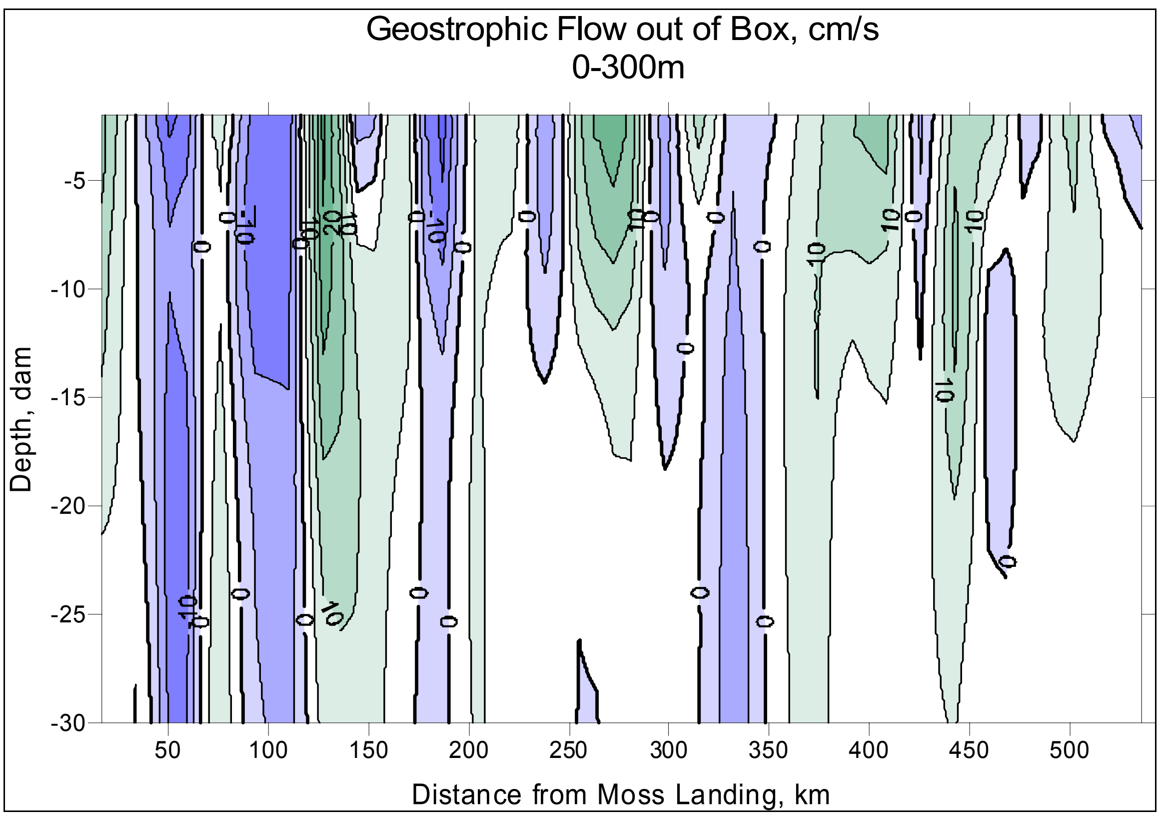


Figure 8

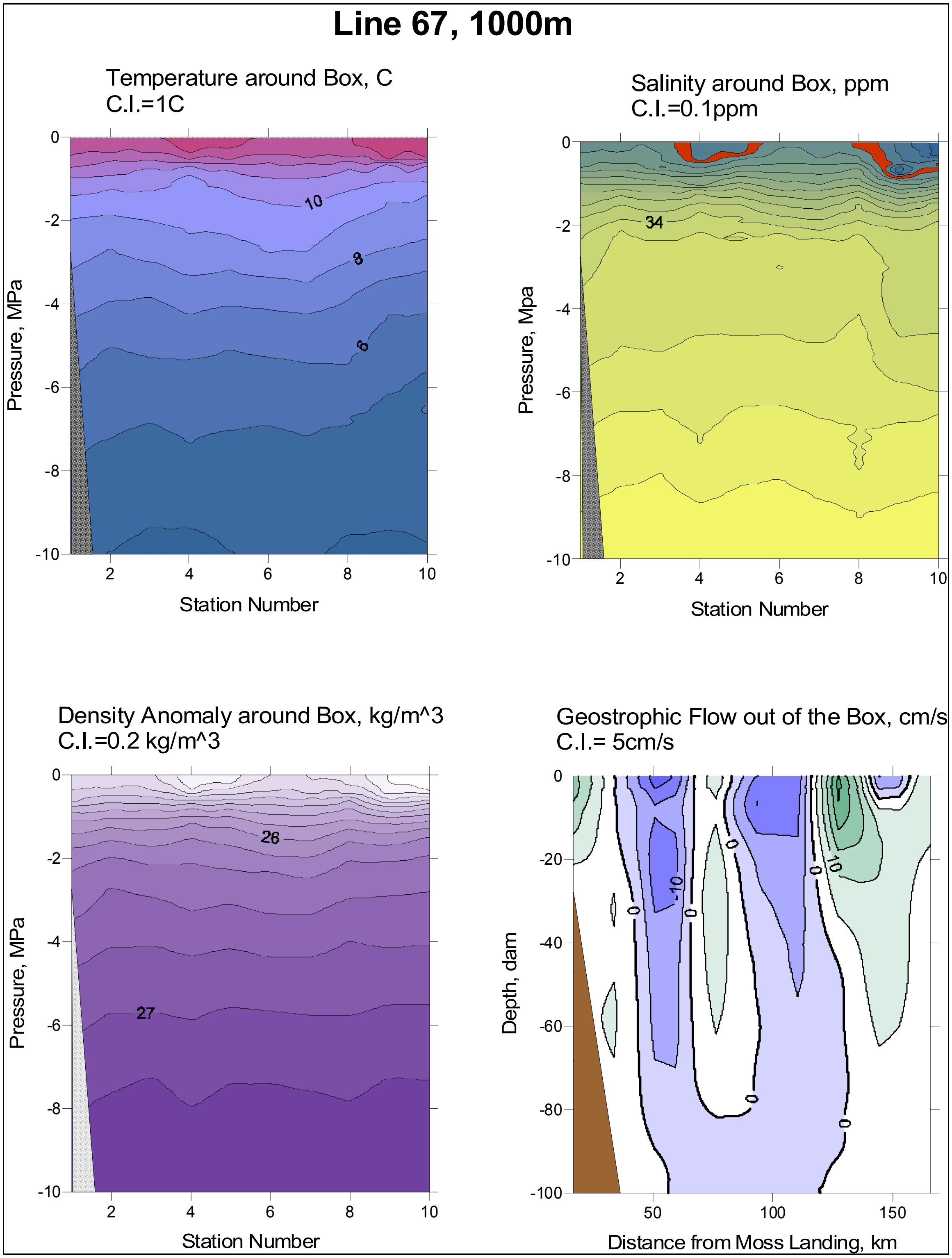

Line 67, 1000m
Temperature around Box, C
C.I.=1C
Pressure, MPa
Station Number
Salinity around Box, ppm
C.I.=0.1ppm
Pressure, Mpa
Station Number
Density Anomaly around Box, kg/m^3
C.I.=0.2 kg/m^3
Pressure, MPa
Station Number
Geostrophic Flow out of the Box, cm/s
C.I.= 5cm/s
Depth, dam
Distance from Moss Landing, km

Figure 9

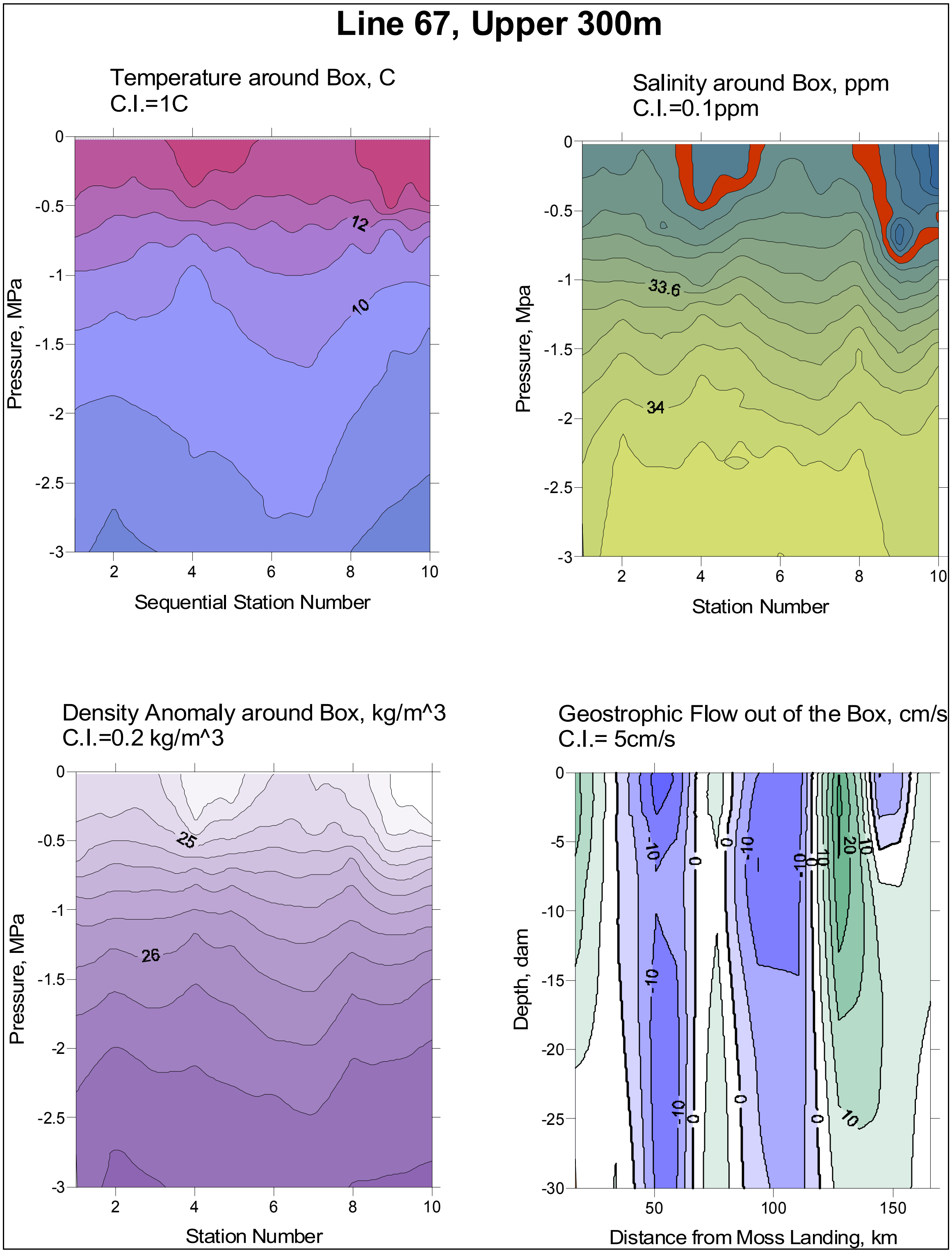
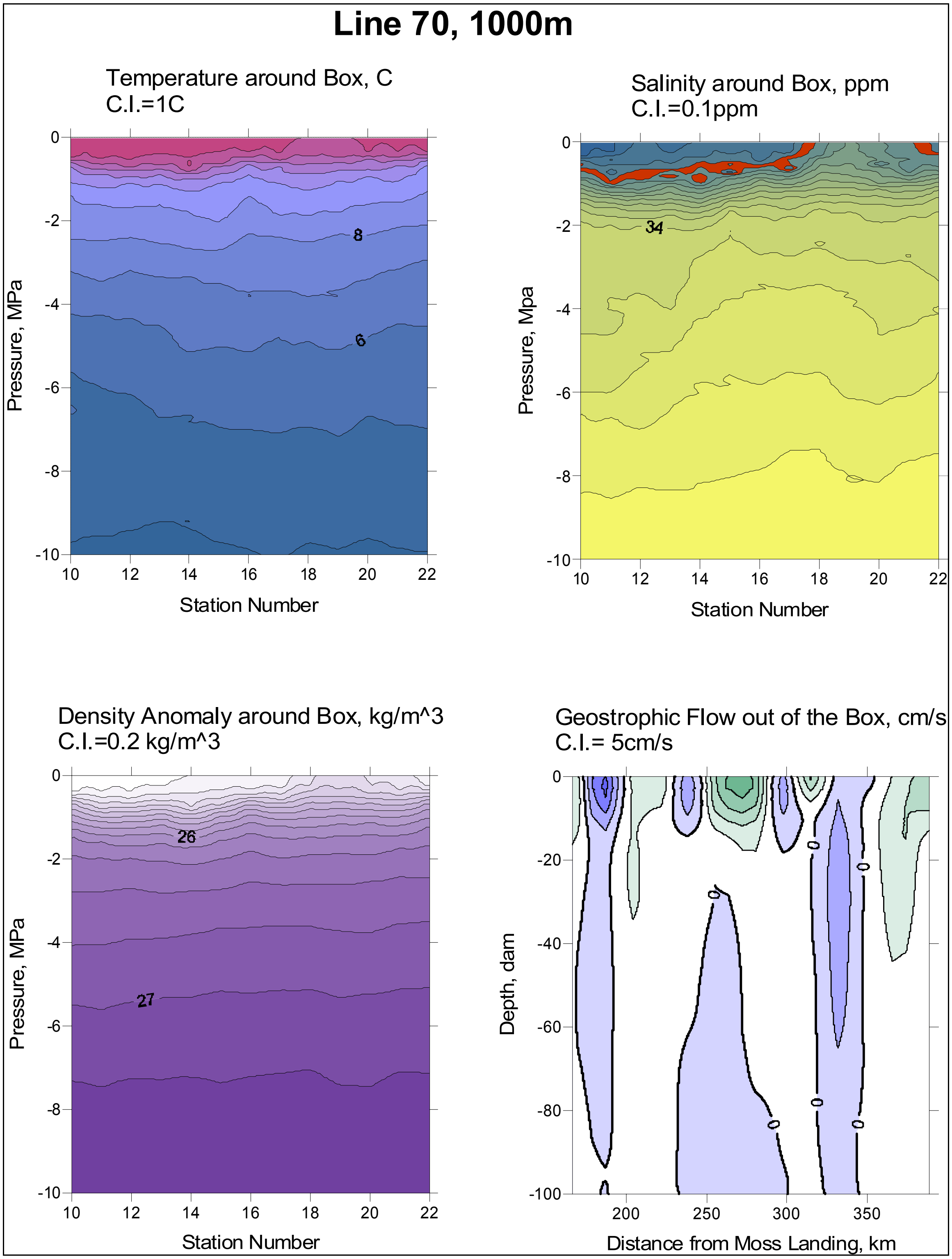
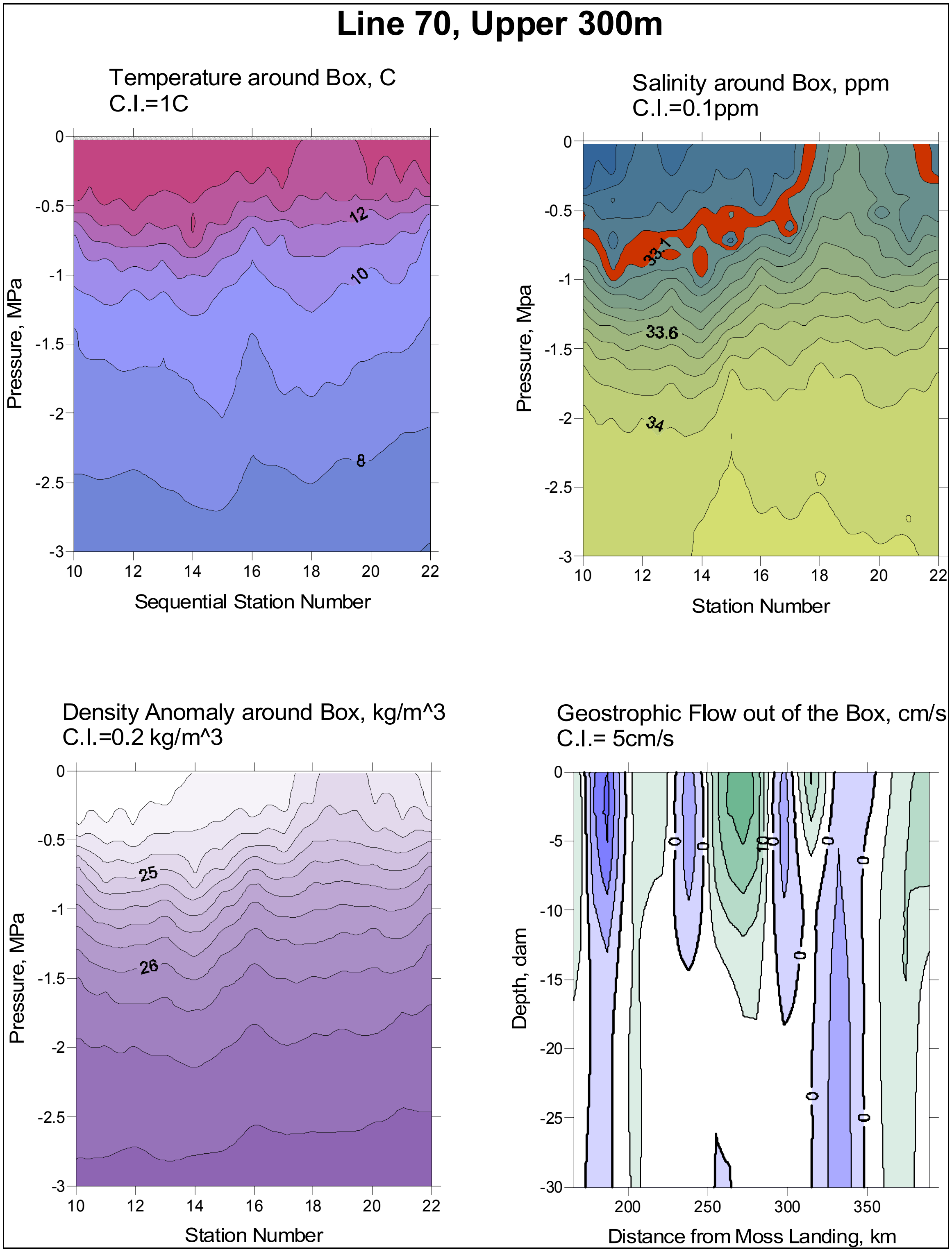

Line 67, Upper 300m
Temperature around Box, C
C.I.=1C
Pressure, MPa
Sequential Station Number
Salinity around Box, ppm
C.I.=0.1ppm
Pressure, Mpa
Station Number
Density Anomaly around Box, kg/m^3
C.I.=0.2 kg/m^3
Pressure, MPa
Station Number
Geostrophic Flow out of the Box, cm/s
C.I.= 5cm/s
Depth, dam
Distance from Moss Landing, km

Figure 10



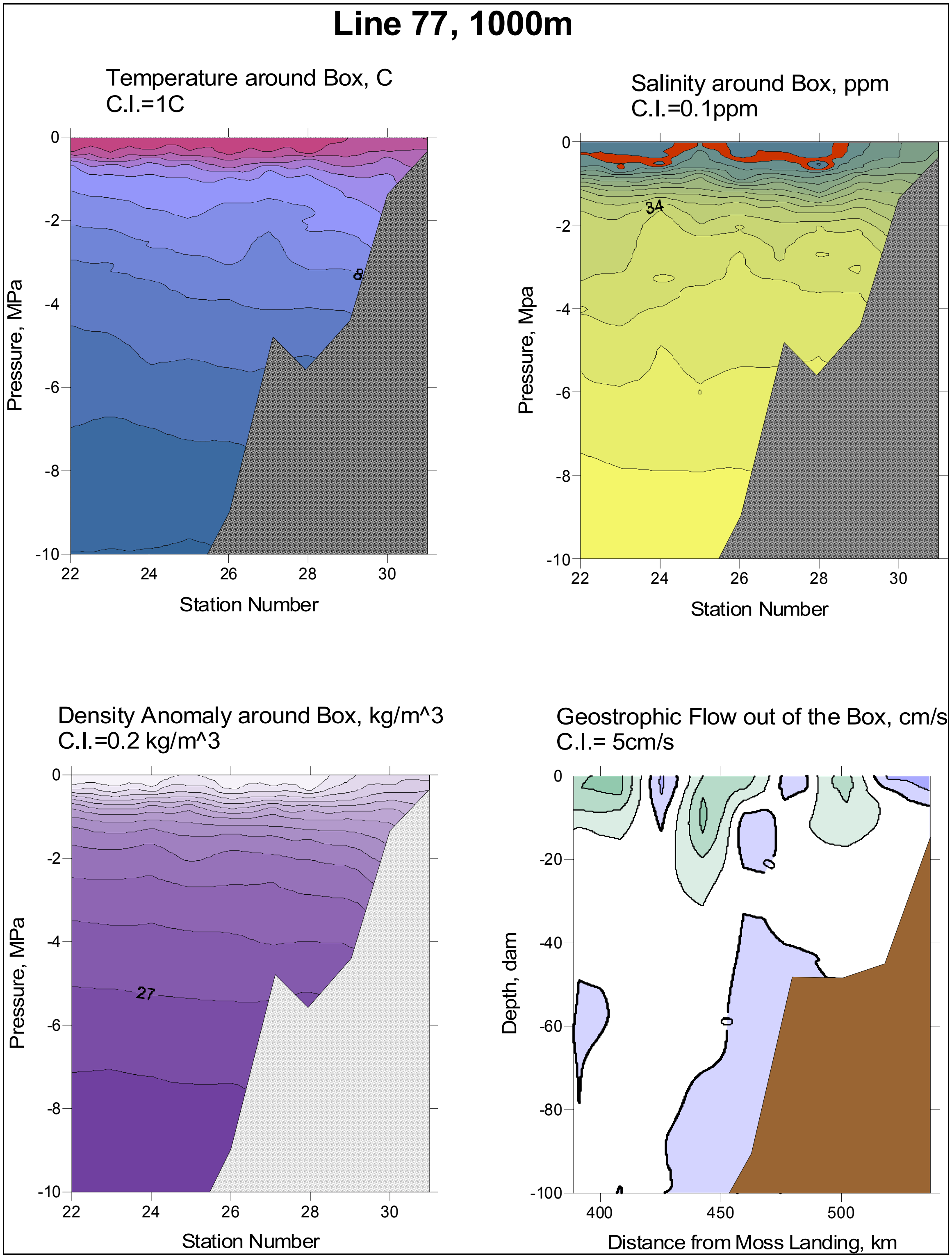
Line 70, 1000m
Temperature around Box, C
C.I.=1C
Pressure, MPa
Station Number
8
6
Salinity around Box, ppm
C.I.=0.1ppm
Pressure, Mpa
Station Number
34
Density Anomaly around Box, kg/m^3
C.I.=0.2 kg/m^3
Pressure, MPa
Station Number
26
27
Geostrophic Flow out of the Box, cm/s
C.I.= 5cm/s
Depth, dam
Distance from Moss Landing, km

Figure 11



Line 70, Upper 300m
Temperature around Box, C
C.I.=1C
Pressure, MPa
Sequential Station Number
Salinity around Box, ppm
C.I.=0.1ppm
Pressure, Mpa
Station Number
Density Anomaly around Box, kg/m^3
C.I.=0.2 kg/m^3
Pressure, MPa
Station Number
Geostrophic Flow out of the Box, cm/s
C.I.= 5cm/s
Depth, dam
Distance from Moss Landing, km

Figure 12



Line 77, 1000m
Temperature around Box, C
C.I.=1C
Pressure, MPa
Station Number
Salinity around Box, ppm
C.I.=0.1ppm
Pressure, Mpa
34
Station Number
Density Anomaly around Box, kg/m^3
C.I.=0.2 kg/m^3
Pressure, MPa
27
Station Number
Geostrophic Flow out of the Box, cm/s
C.I.= 5cm/s
Depth, dam
Distance from Moss Landing, km

Figure 13

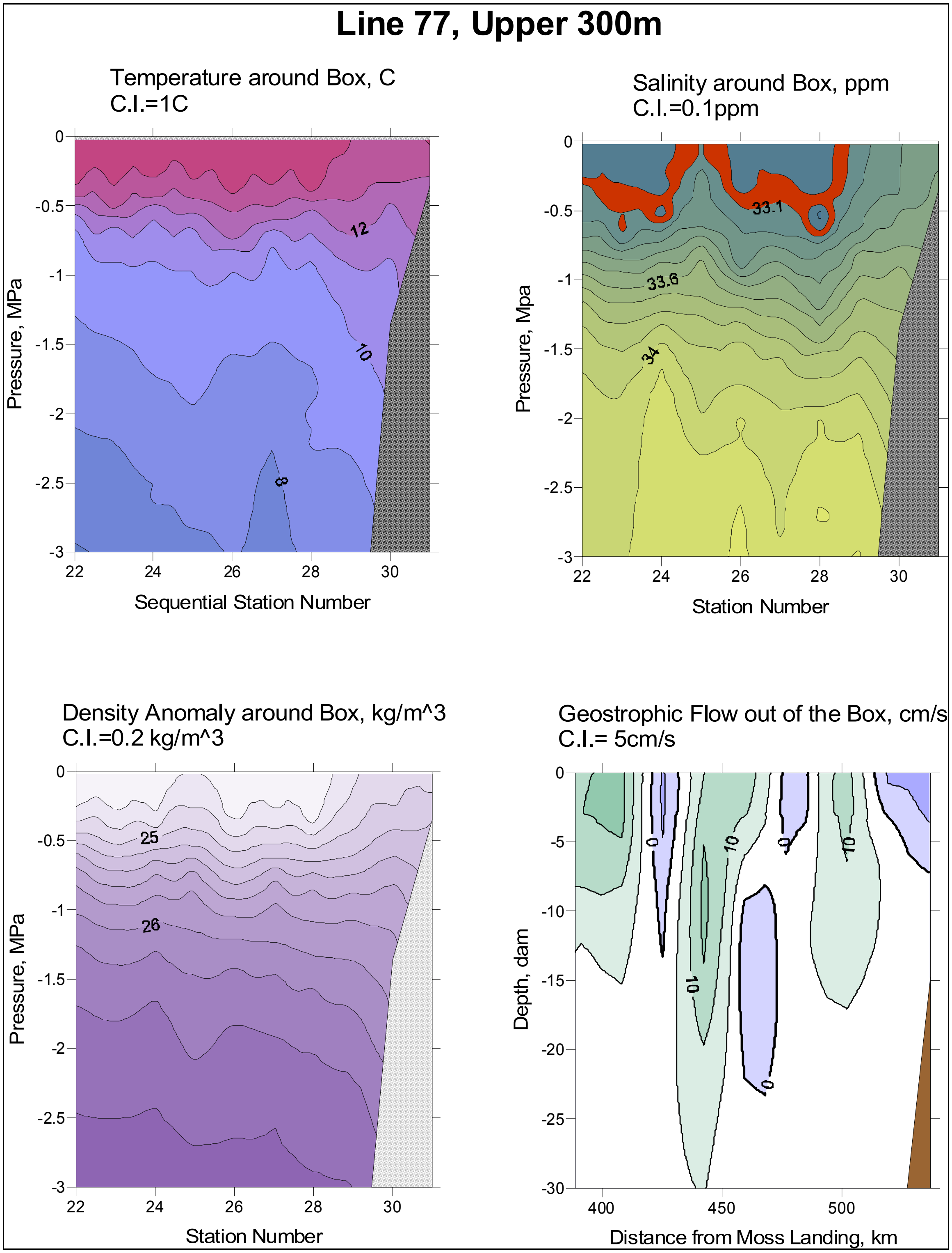

Line 77, Upper 300m
Temperature around Box, C
C.I.=1C
Pressure, MPa
Sequential Station Number
12
10
8
Salinity around Box, ppm
C.I.=0.1ppm
Pressure, Mpa
Station Number
33.1
33.6
34
Density Anomaly around Box, kg/m^3
C.I.=0.2 kg/m^3
Pressure, MPa
Station Number
25
26
Geostrophic Flow out of the Box, cm/s
C.I.= 5cm/s
Depth, dam
Distance from Moss Landing, km
0
10

Figure 14