I. INTRODUCTION

The California Current System (CCS) is a classical eastern boundary current (EBC), forming the eastern segment of the North Pacific Sub-tropical gyre along the west coast of North America. Influenced by large-scale wind forcing, the strength and upwelling characteristics of the CCS vary greatly with the seasonal dominance of either the North Pacific high (summer) or the Aleutian low (winter).

The CCS is comprised of several large-scale circulations and three separate types of water masses (Hickey, 1998). The dominant flow is known as the California Current (CC), which is a broad (~1000km), equatorward surface current (0-300m). The CC can be characterized as colder, fresher Pacific sub-Artic water in a relatively slow year round flow (~10-30 m/s), with a core between 300-400 m (Lynn and Simpson, 1982). Below the CC is the California Undercurrent (CUC) a narrow (~10-40 km), relatively weak (~2-10 cm/s), poleward subsurface flow which follows the continental slope from the Baja peninsula north past the Columbia River. The CUC is generated due to the pressure gradients created by the natural distribution of warmer, higher salinity waters to the south and colder, fresher water to the north. Originating in the eastern equatorial Pacific, the CUC brings warmer, more saline Its strength, location and core depth vary seasonally due to the variability in wind stress and wind stress curl (Hickey, 1979). A stronger CC will result in a weaker, deeper CUC. It is usually strongest near 300meters depth. The third, and least studied, flow is known as the Inshore Current, or Davidson Current (DC). This is a relatively weak (~5 cm/s) surface, poleward flow found near the coast north of Point Conception. Some studies suggest that the DC is a result of the CUC shallowing in late fall when the CC is weakest (Pavlova, 1966; Huyer and Smith, 1974). Others believe the

DC is created by the presence of warmer, fresher water along the coast during the non-upwelling season. An examination of the dynamic heights, and related geostrophic currents, during this period show a poleward current inshore of the CC, along the coast.

The introduction of satellite imagery and in depth observational research has shown that the CCS is not the stable, well-defined system previously defined. Instead, it is characterized by large fluctuations in both time and space (Chelton, 1984). Meanders, eddies and filaments influence the large-scale flow and drastically effect the physical characteristics of the CCS. An evaluation of the physical features, i.e. temperature, salinity and density, can provide a more detailed image of the state of the CCS for a given period.

II. PURPOSE

The purpose of this project is to study the hydrographic properties of the CCS in the Naval Oceanographic Office's Central California region (Figure 1) for the December 2001 data set. Data from conductivity, temperature and depth (CTD) casts will be used to calculate dynamic heights, properties on sigma-levels and surface characteristics. From this data a qualitative evaluation will be made to determine current direction and strength, origin of water properties and a general interpretation of the state of the CCS during the data collection process.

III. PROCEDURE

A. Data Collection

Data was obtained within the CenCal region from 28 November to 11 December 2001 during a NAVO sponsored cruise. For this project, 59 of the 66 stations in the CenCal Box were evaluated (highlighted in Figure 1). CTD and ADCP data were collected at each station. The Sea-Bird 911 plus CTD was used to provide continuous measurements of conductivity, temperature and depth at a rate of 24 Hz. CTD casts were made to a pressure of ~1000 dbar, except for stations that were limited by shallow topography. Post cast processing of the data created files grouping the data into 2 dbar bins consisting of time, latitude, longitude, pressure, primary and secondary temperature, primary salinity, density, and dynamic height. The hull mounted ADCP provided continuous currents measurements below the ship.

B. Data Processing

Examination of the dynamic topography gives an accurate first guess for the current strength and direction. Dynamic heights provide oceanographers with a parameter that takes into account horizontal differences in density between two levels. The density difference reflects a change in dynamic topography that provides a measure of the horizontal pressure gradient force. When determining the current direction a reference level is assumed to be a “depth of no motion”. A change in dynamic height between the two levels will generate a horizontal pressure gradient, and subsequent geostrophic current that is referenced to the “depth of no motion”. Post cast processing computed the dynamic heights for each pressure level of the data set. To determine the dynamic topography between two levels a Matlab program was used to calculate the difference in dynamic heights between two levels. A useful explanation of the equations and parameters for determining dynamic height can be found in (Pickard and Emery, 1982).

Another convenient tool used for examining the physical characteristics of the water masses and currents was the isopycnal surfaces, or sigma-levels. It is assumed that a water mass will flow parallel to a constant sigma-level (Pickard and Emery, 1982). The density of seawater is a function of salinity, temperature and pressure ($\rho = \rho(S,t,p)$). Potential temperature was used with a reference pressure of p=0. It is standard practice to express density in convenient four-digit format by subtracting 1000 kg/m^3:

$$\rho_\theta = \rho(S,t,0)$$

$$\sigma_\theta = \rho_\theta - 1000 \text{ kg/m}^3$$

An additional Matlab program read the data and selected bins whose density matched the standard sigma-levels of 25.8, 26.2, and 26.7 kg/m^3. These points were placed into a new data file along with corresponding salinity, temperature and pressure data.

Both the dynamic topography and sigma-level contours were created using Surfer 7.0. The program interpolates the data for areas that did not provide actual CTD cast data. Bottom topography and blanking methods were used to mask data sparse regions where the interpolations would give an inaccurate depiction of the actual physical properties.

IV. DATA ANALYSIS

A. Dynamic Topography

<u>Dynamic Height 0/1000</u>

The dynamic topography displayed in Figure 2 gives a general overview of the circulations through the entire layer of the CCS. A dynamic trough dominates the overall contour and directs the flow in the region. Because the CC is the only equatorward flowing current is easily distinguished on the western edge of the contour. Lower dynamic heights are expected in the CC because is contains colder water. Both the CUC and DC influence the weak poleward flow along the coast. Also present is a relatively strong onshore flow into the Monterey Bay region. This could possibly be an area where the CC has turned onshore and is redirected poleward by either the CUC or the DC. A more in depth look into the different layers of the system will give a better understanding of the currents present and the origin of the water masses.

Dynamic Height 0/200

Figure 3 depicts the upper layer dynamic topography of the CCS, which provides a useful representation of the surface currents. Although the currents and dynamic trough are similar to those in Figure 2, an examination of the contour spacing reveal that the 0/200 level currents are much weaker. A CC meander near 37N, 124W and a significant onshore flow at the lower end of the contour are present. The weak poleward flow along the coast denotes the presence of the DC. The onshore flow bringing water into the Monterey Bay region may be creating a piling up. This concentration of mass may increase dynamic heights in the area and set up a source region for the DC.

Dynamic Height 200/500

The middle layer of the region represented in Figure 4 reveal the heart of the CUC. Because the DC is a surface current, the relatively strong poleward flow along the coast is attributed to the large-scale temperature and salinity gradients associated with driving force of the CUC. The CC is usually confined to the upper 500m, with a maximum near the surface. The 200/500 contour shows a substantial decrease in the gradient related to the CC meander. Evidence that the CC is linked to the onshore flow is not possible due to the limited data set. The origin and steering mechanism for this flow is difficult to deduce and remains unsolved throughout the analysis.

Dynamic Height 500/1000

Below 500m the entire CCS deteriorates due to a weakening of both internal (i.e., sal, temp) and external (wind) forcing mechanisms. Both the CC and the CUC are still apparent in Figure 5. The dynamic trough has broken down. Deeper in the system the topography is beginning to impede on the project domain and breakdown the dynamic trough. The CUC is influenced more by this effect since it is trapped along the coast.

B. Sigma-level Analysis

Pressure on 25.8 kg/m^3

A contour of the pressure field on a sigma-level provides an additional tool to examine the current strength and direction. Figure 6 depicts the pressure on the 25.8 kg/m^3sigma-level. Because the pressure on this surface range from 50 to ~80 dbar it is possible to compare Figure 6 to the 0/200 dynamic height contour(Figure 3). Both figures represent the flow in the upper level region of the CCS. The sigma-level contour is more localized and is a better indicator of the currents in a small layer. However, because this is a qualitative analysis actual current velocities were not computed and a comparison can only be made in terms of current direction. A dome of low pressure dominates the contour creating a strong signature for the DC. This dome corresponds to the dynamic trough seen in Figure 3. Also evident is a substantial onshore flow, which shows a link between the CC and the DC. Several small scale eddies in the vicinity of the Monterey Bay reveal the variability in the upper level dynamics.

Pressure on 26.2 kg/m^3

Figure 7 depicts the pressure levels ranging from 90 to 150 dbar for the 26.2 kg/m^3sigma-level. This contour can also be compared to Figure 3, however because it is deeper in the layer the poleward current along the coast is related to the CUC vice the DC. Additionally, because the CUC is a stronger current the gradient associated with the poleward flow is greater. The tightest gradients are found in the vicinity of the onshore flow in the southern portion of the contour. Again, the plot shows a connection between the equatorward CC current and the poleward CUC via the onshore flow. The small-scale variability near Monterey Bay is significantly reduced from that observed on the 25.8 sigma-level contour.

Pressure on 26.7 kg/m^3

Being the deepest of the standard sigma-levels Figure 8 represents the 26.7 kg/m^3contour with pressure ranging between 280 and 335 dbar. The low-pressure dome is more intense than in the upper layers. The entire layer shows an increase in meandering and tighter gradients associated with stronger currents. The onshore flow has become more meridional and is integrated into the CUC flow. A link may still exist between the CC and the CUC, but it is outside of the domain of data available. North of Pescadaro Point the CUC has veered away from the coast. Further study into the physical characteristics creating the high-pressure sink would be required to classify the mechanism creating this effect.

Salinity on 25.8 kg/m^3

The salinity analysis on a sigma-level gives an indication of the origin of the water mass. In conjunction with the contour plots the density-salinity plot (Figure 9) is a useful aid for classifying water properties. Figure 10 shows evidence of mixing between equatorial Pacific water and sub-arctic Pacific waters associated with the CC and DC, respectively. The maximum salinity values along the coast correlate to the transport of high salinity water by the DC. In the region of the CC meander the intense salinity gradient depicts a strong boundary between the water masses. Additional analysis of the CTD cast plots (not shown) show that this could be a pool of fresh, sub-artic water created by subduction of the saltier equatorial waters.

Salinity on 26.2 kg/m^3

Figure 11 shows relatively high salinity values along the coast are associated with the advection of equatorial Pacific water by the CUC. The analysis of the pressure fields in Figure 7 reveal a strong poleward flow in the vicinity of the salinity max, which validates this finding . Most notably though is the small pool of fresh water in the western region of the project domain. As was the case on the 25.8 sigma-level contour this effect is due to subduction of equatorial waters. The subduction is created by an increase in the density of the equatorial water through cooling. Because it has become denser it flows under the sub-artic water trapping the fresh water.

Salinity on 26.7 kg/m^3

The salinity analysis on the 26.7 kg/m^3 (Figure 12) reveals a distinct boundary between the sub-artic and equatorial waters. The core of the CUC is usually found near 300m, which corresponds to the pressure range of this contour. Both the dynamic topography for 200/500 and the pressure contour for this sigma-level show a relatively strong CC. The strength of the two currents inhibits mixing between the water masses. It is also significant to mention that this level contains the saltiest water. Research has shown that the CCS is different from other boundary currents because salinity increases with depth rather than decrease (Wooster and Reid, 1963) cited (Batten et al, 1995).

C. Surface characteristics

<u>Salinity and Temperature</u>

The final evaluation of CTD data for the project involved examining the surface temperature and salinity, Figure 13 and 14, respectively. The data from the 2mb bin was used for the contours. Unexpectedly, the surface temperature was a poor indicator of the current dynamics. Warm water usually relates to less dense water and a rise in the dynamic heights. However, the warmest waters are in the region of the dynamic trough seen in Figure 3. The coldest waters are seen near the Monterey Bay and the mouth of San Francisco Bay, which does not correlate with the higher dynamic heights believed to be forcing the DC. The surface salinity contour proved to be a decent indicator of fresh water signatures. It shows that along the coast, especially near the San Francisco Bay, there is sufficient fresh water runoff to influence the surface salinity. Relatively fresh water is less dense and should correspond to higher dynamic heights. The pool of fresh water in the region of the CC meander corresponds well with the dynamic topography. Outside of regions with large salinity gradients the surface salinity plot provides little useful information.

D. ADCP comparison

Up to this point all the contours and evaluations have been on data collected by the CTD. A final qualitative comparison of the data was prepared using the hull mounted ADCP. Figure 15 depicts the ADCP collected over the cruise period for 25 to 75 meters depth. This layer corresponds to those evaluated in the 0/200 dynamic topography and the 25.8 kg/m^3 sigma-level pressure contour. The ADCP measurements clearly show the equatorward flow of the CC along 124W longitude, as well as the signature of a meander in the current near 37N. Also evident is the poleward flowing DC and an onshore current west of the Monterey Bay. Through the center of the plot, in the region of the dynamic trough, weak ADCP reading agree with weak dynamic height and pressure gradients. The ADCP data provides a reasonable validation of accuracy of the CTD measurements.

V. CONCLUSION AND RECOMMENDATIONS

The evaluations of the physical properties measured by the CTD provide significant insight into the origins of water masses and forcing mechanisms of the CCS. An important validation of findings was accomplished by analysis of several different sets of data, by dividing the CCS into layers and using entirely separate physical characteristics (topography vs. sigma-levels). Comparisons between the dynamic topography and the pressure on sigma-levels were useful when resolving the presence of currents. Coupling this data with the salinity on sigma-levels proved useful when determining the origin of water masses through their salinity signature. Unfortunately the surface analysis did not prove as useful as expected, with the exception of regions of strong salinity gradients. The only mysteries found during the analysis were the onshore flow and the true origin of the relatively fresh water pool found on the 26.2 kg/m^3 sigma-level analysis. The two limiting factors of this problem were the boundary of the project domain and the inherent time separation between CTD casts. Enlarging the data collection area would solve the first factor, but would increase the time required and more importantly increase the cost of the experiment. Using several ships could reduce the time difference between casts. While saving time this solution is unfeasible due to the drastic increase in cost.

This project utilized data from the winter season of the CCS. Future projects could be performed on seasonal data corresponding to the upwelling season to provide a look into the seasonal variability of the CCS. It would also be interesting to investigate additional physical properties including oxygen content, phosphates and other chemical properties to see how they vary seasonally throughout the layer of the system.

VI. REFERENCES

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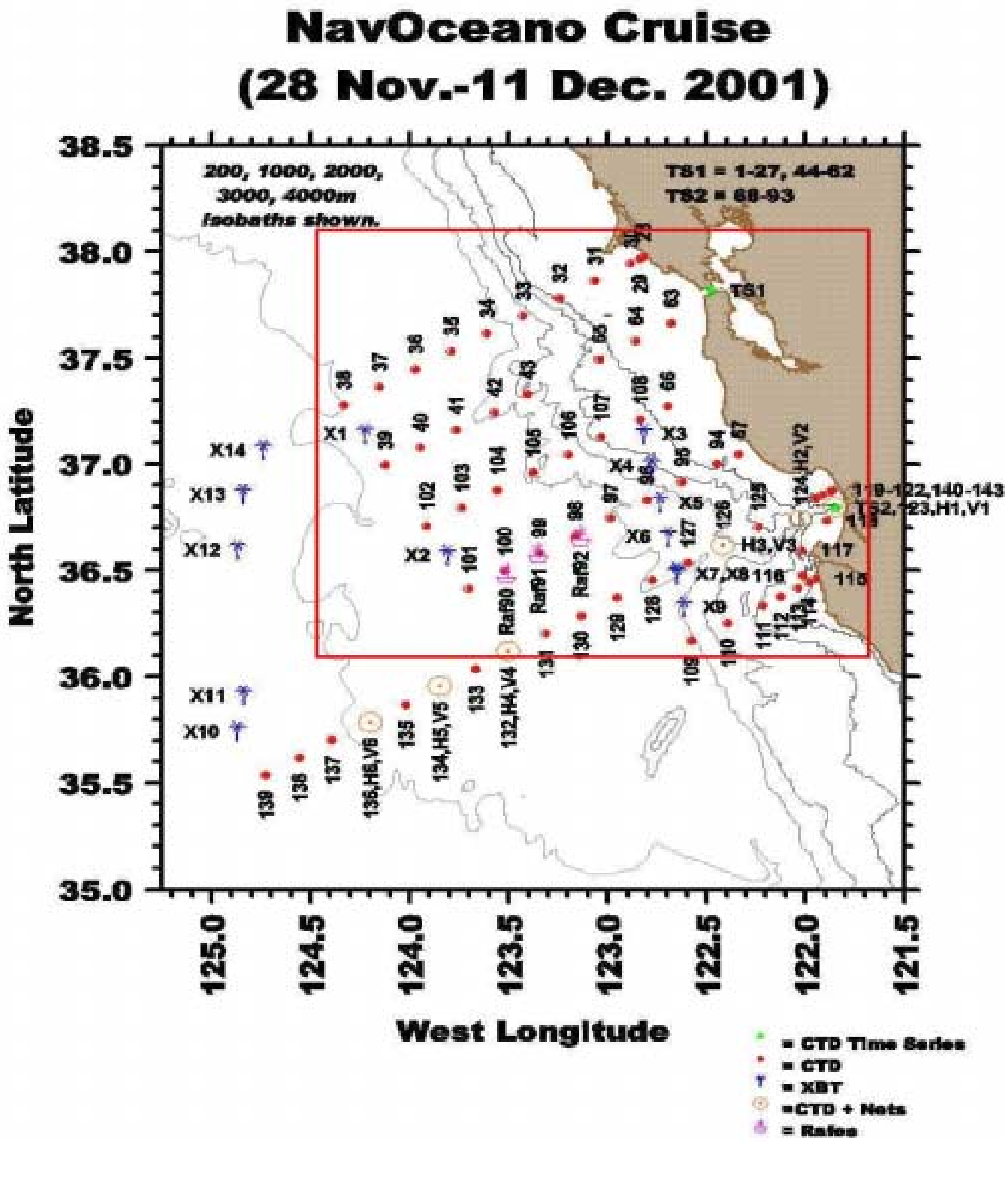
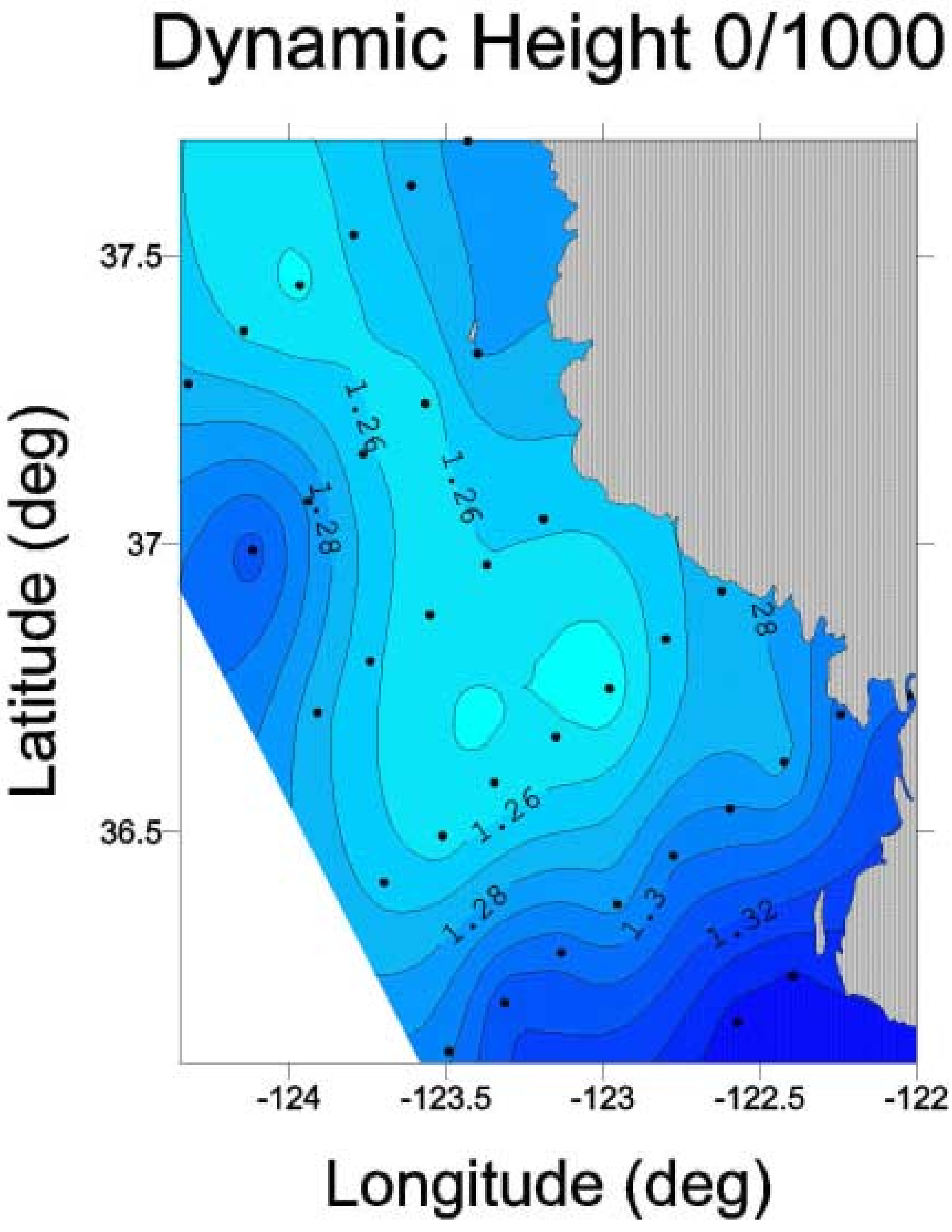
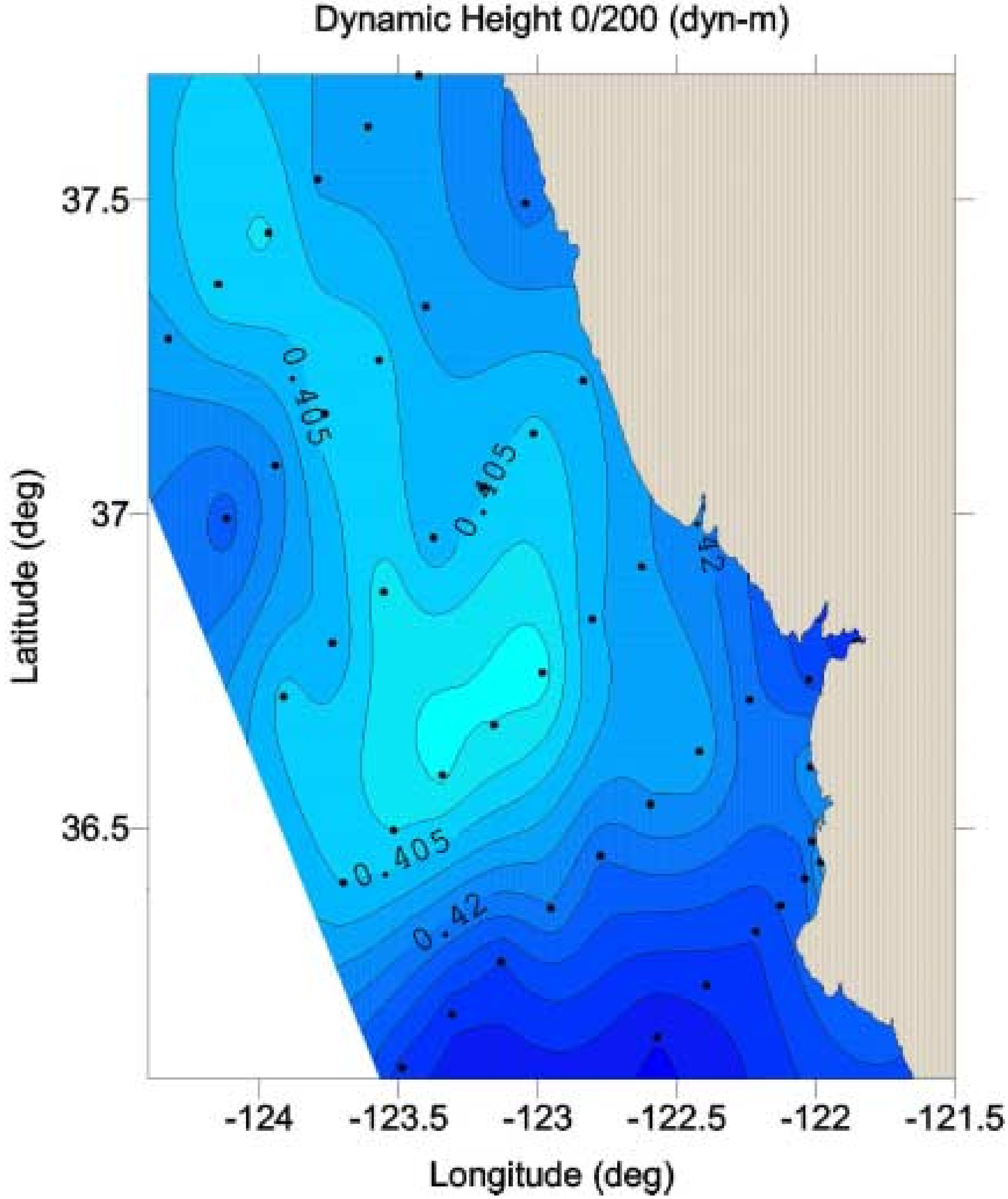
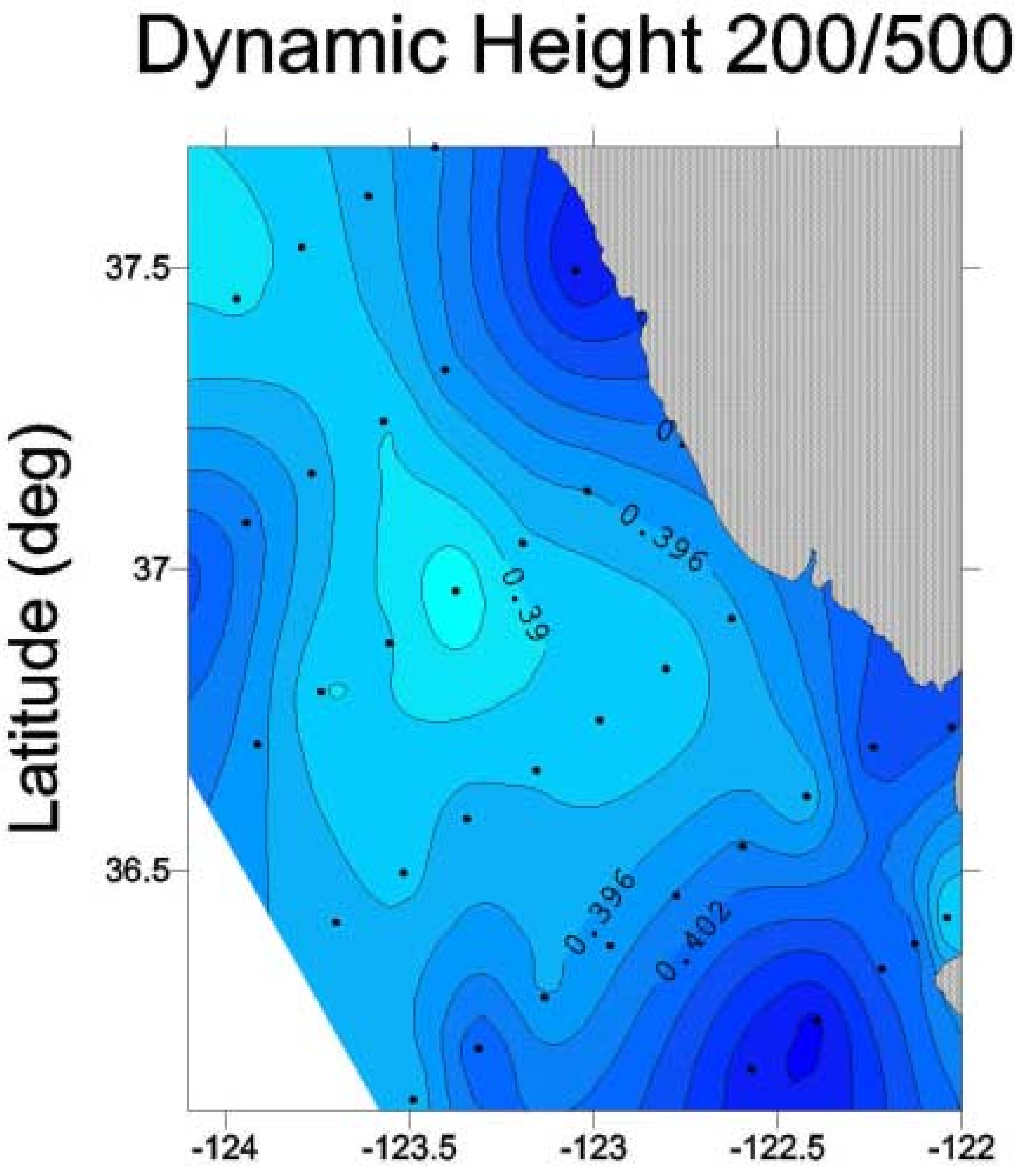

NavOceano Cruise
(28 Nov.-11 Dec. 2001)
North Latitude
West Longitude
200, 1000, 2000, 3000, 4000m Isobaths shown.
TS1 = 1-27, 44-62
TS2 = 68-93
= CTD Time Series
= CTD
= XBT
=CTD + Nets
= Rafos



Dynamic Height 0/1000
37.5
37
36.5
Latitude (deg)
-124
-123.5
-123
-122.5
-122
Longitude (deg)
1.26
1.26
1.28
1.26
28
1.28
1.3
1.32


Dynamic Height 0/200 (dyn-m)
37.5
37
36.5
Latitude (deg)
-124
-123.5
-123
-122.5
-122
-121.5
Longitude (deg)
0.405
0.405
0.405
0.42
.42


Dynamic Height 200/500
Latitude (deg)
37.5
37
36.5
Longitude (deg)
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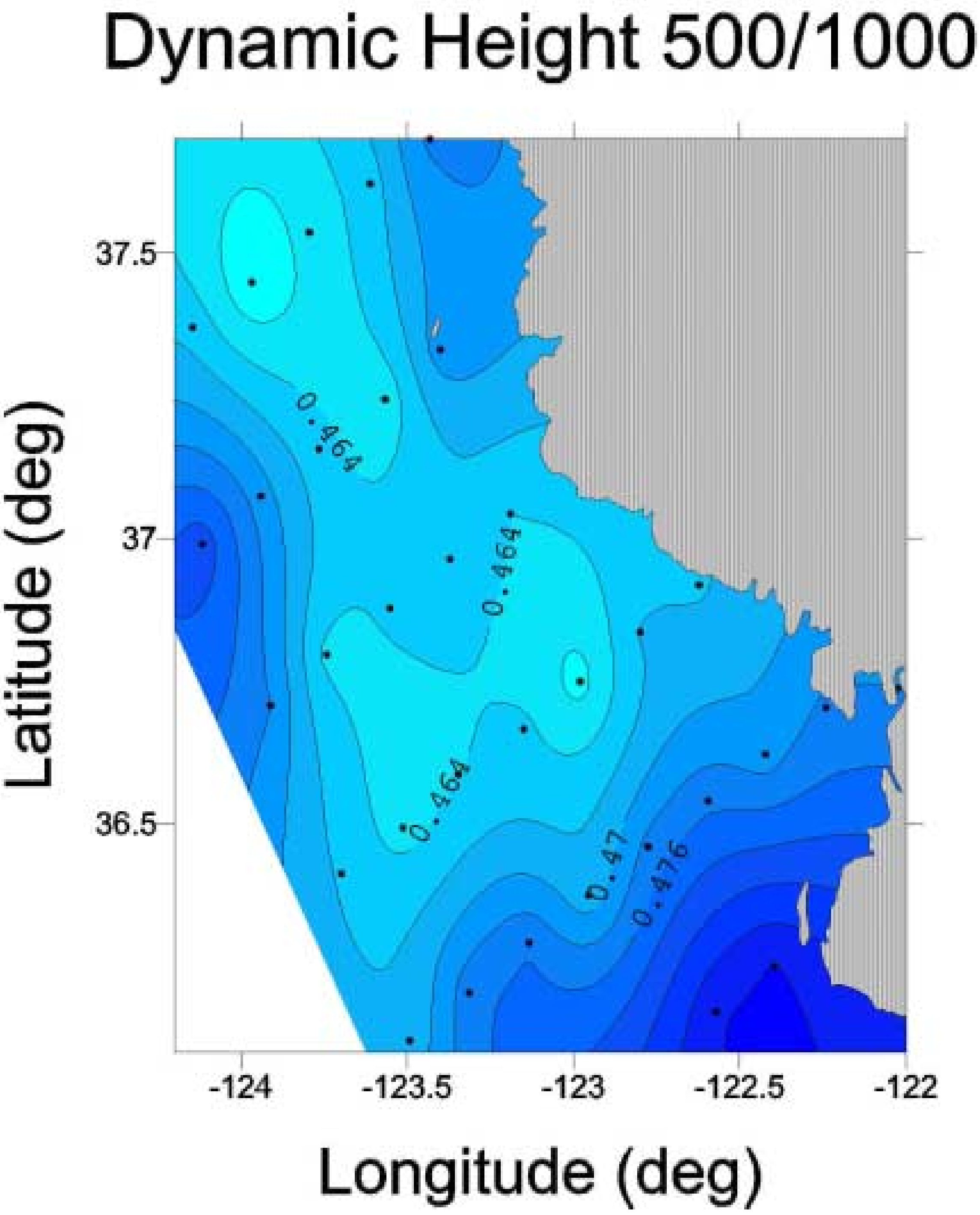
-123.5
-123
-122.5
-122
0.396
0.39
0.396
0.402


Dynamic Height 500/1000
37.5
37
36.5
Latitude (deg)
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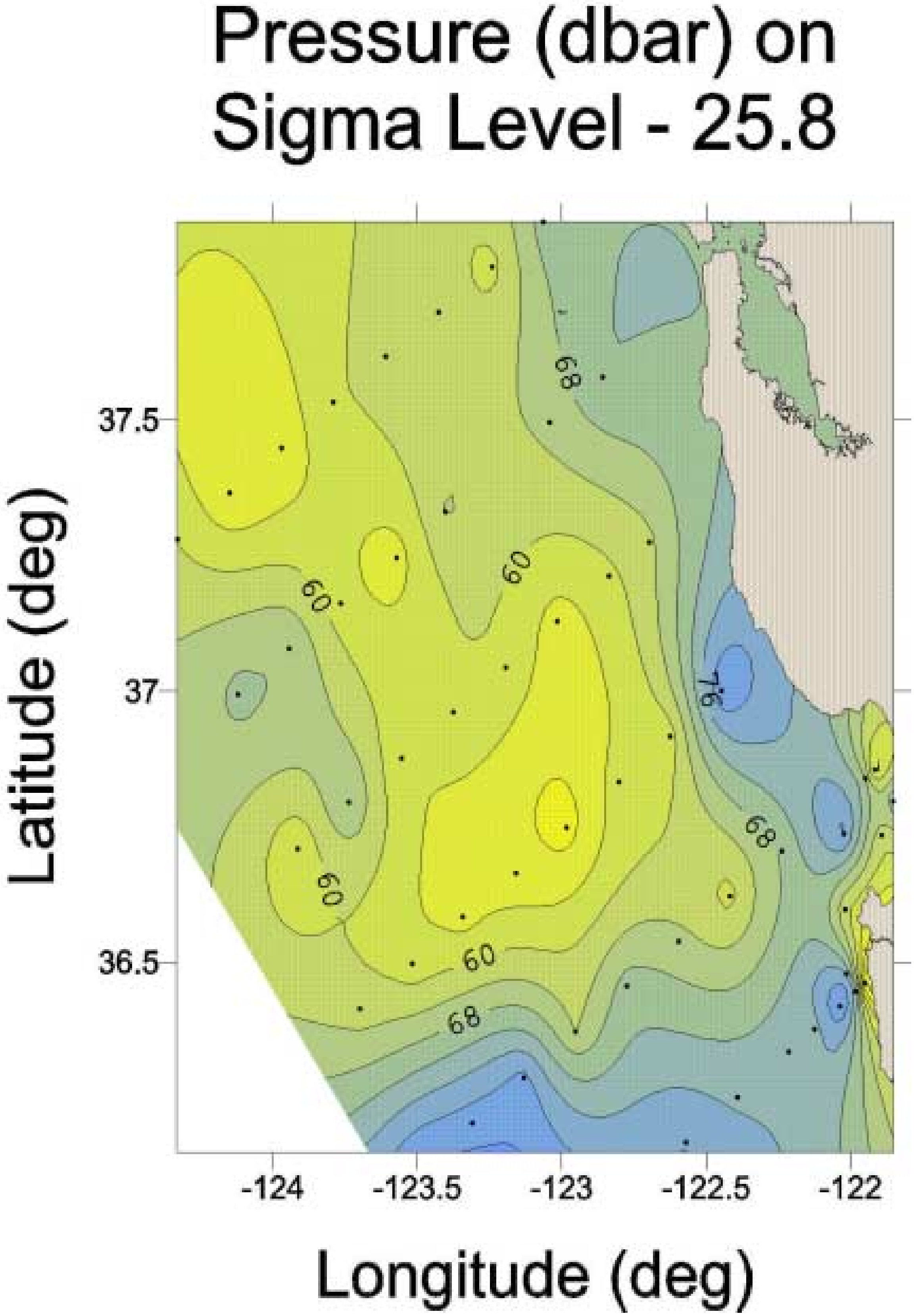
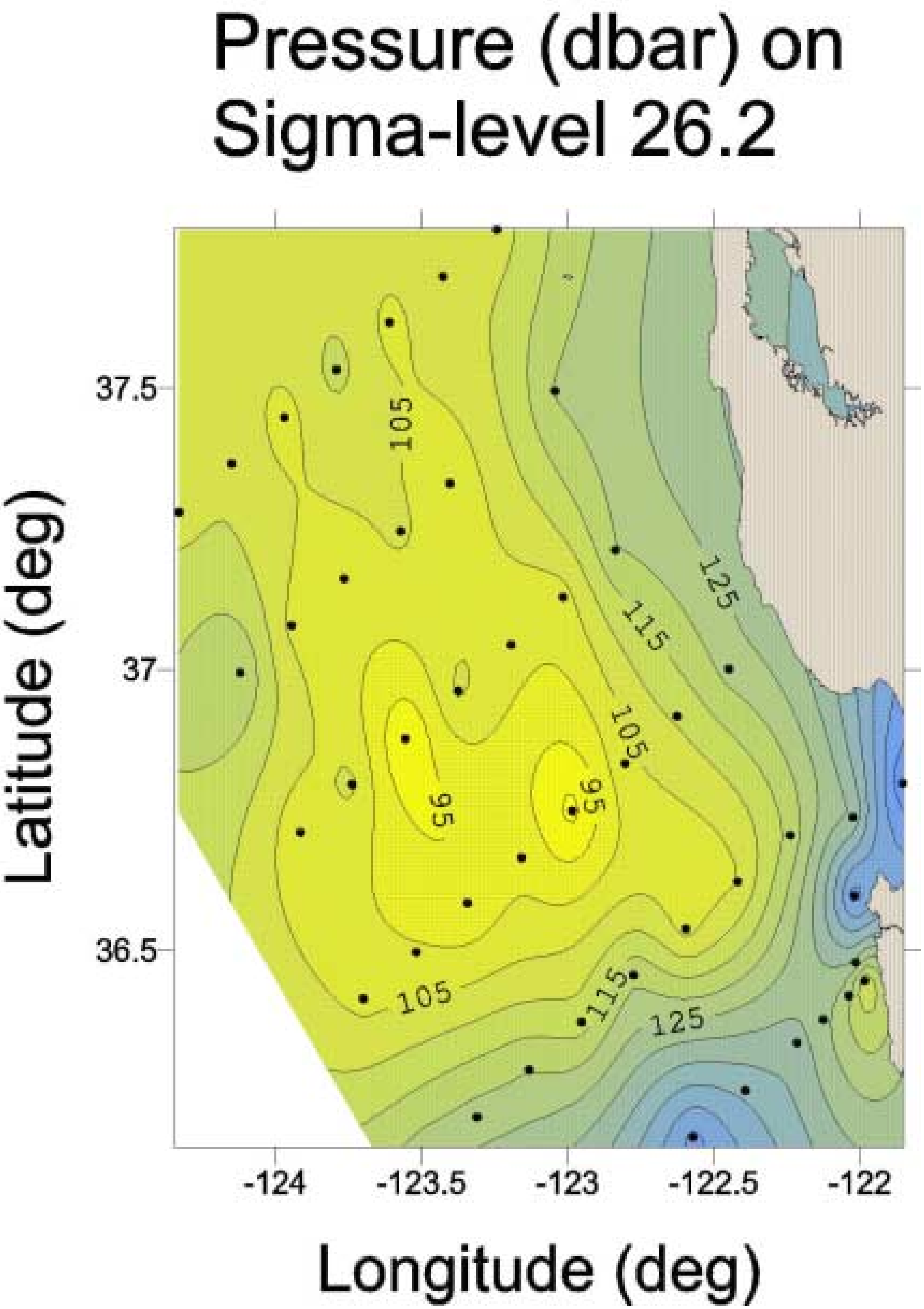
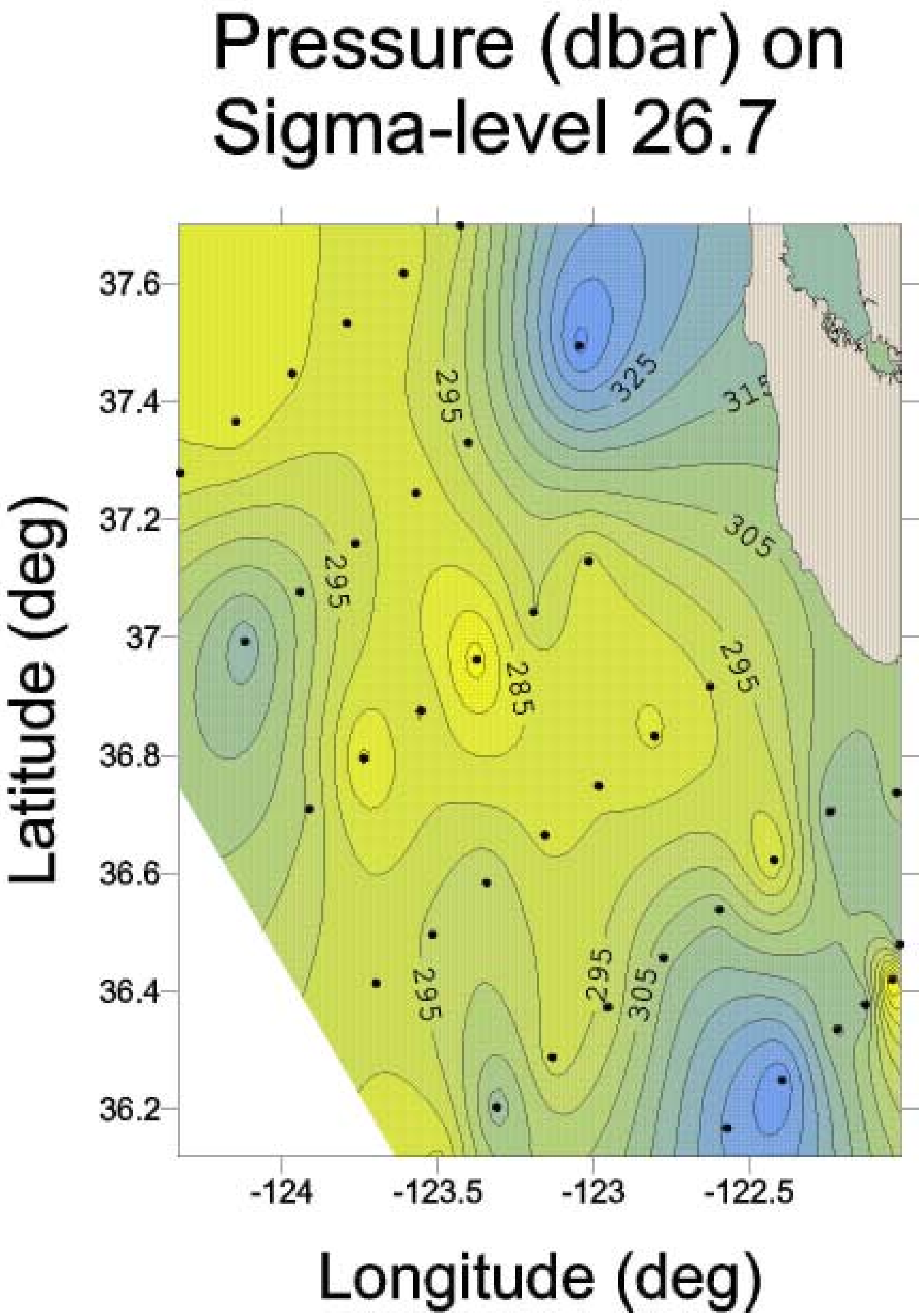
0.464
0.464
0.47
0.476
-124
-123.5
-123
-122.5
-122
Longitude (deg)

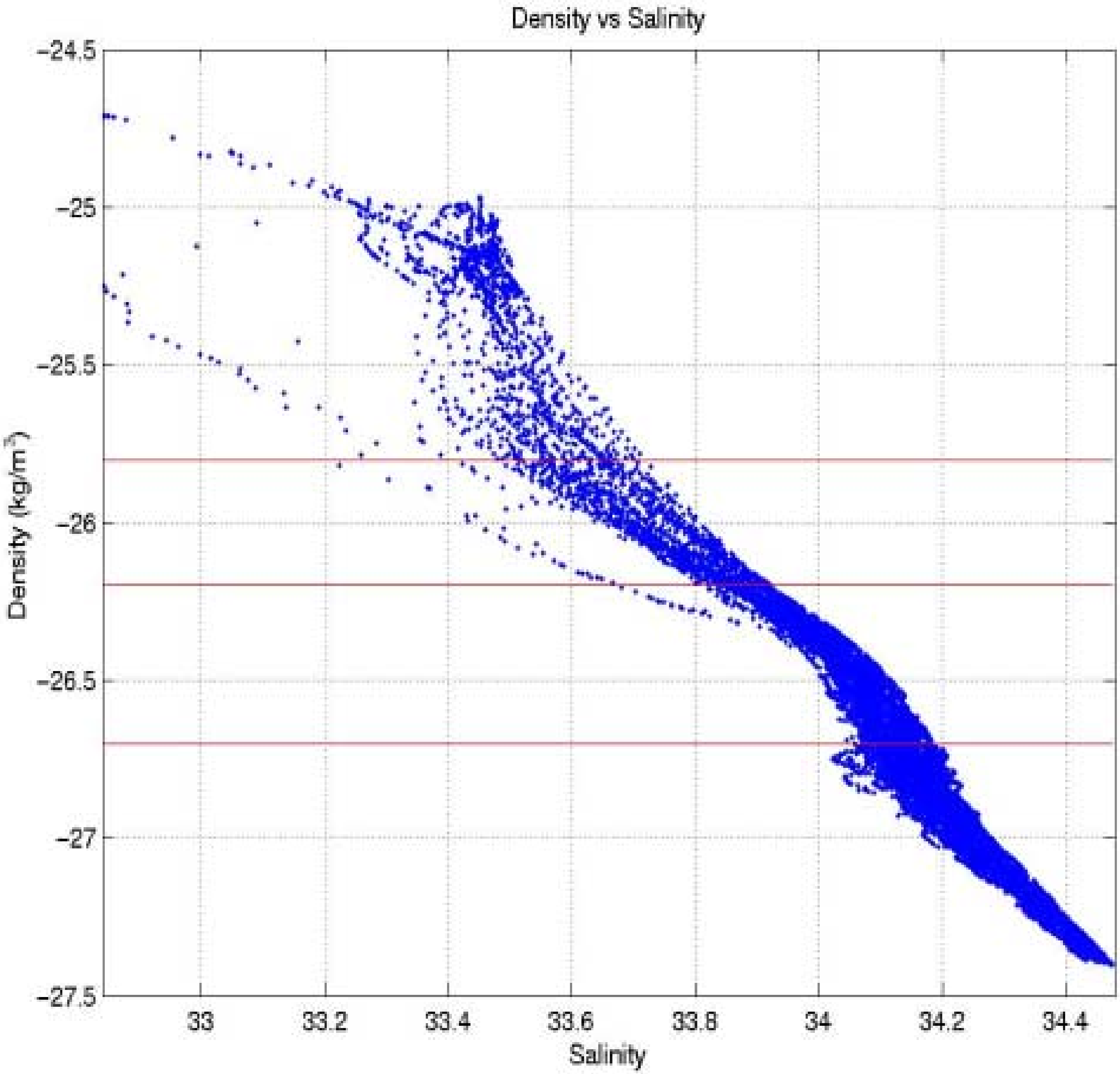

Pressure (dbar) on
Sigma Level - 25.8
37.5
37
36.5
-124
-123.5
-123
-122.5
-122
Latitude (deg)
Longitude (deg)
68
60
60
60
76
68
60
60
68



Pressure (dbar) on
Sigma-level 26.2
37.5
37
36.5
-124
-123.5
-123
-122.5
-122
Latitude (deg)
Longitude (deg)
105
125
115
105
95
95
105
115
125

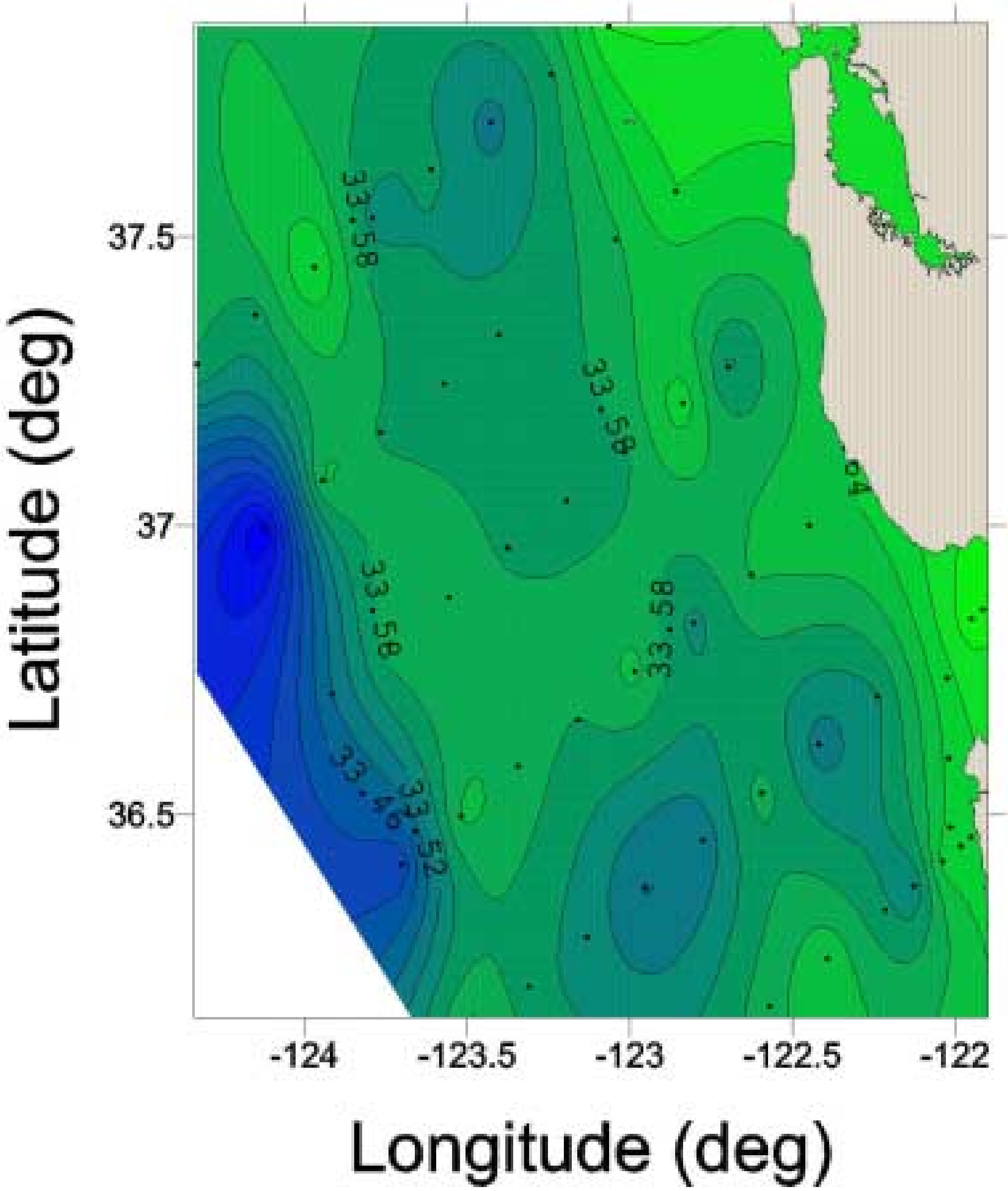


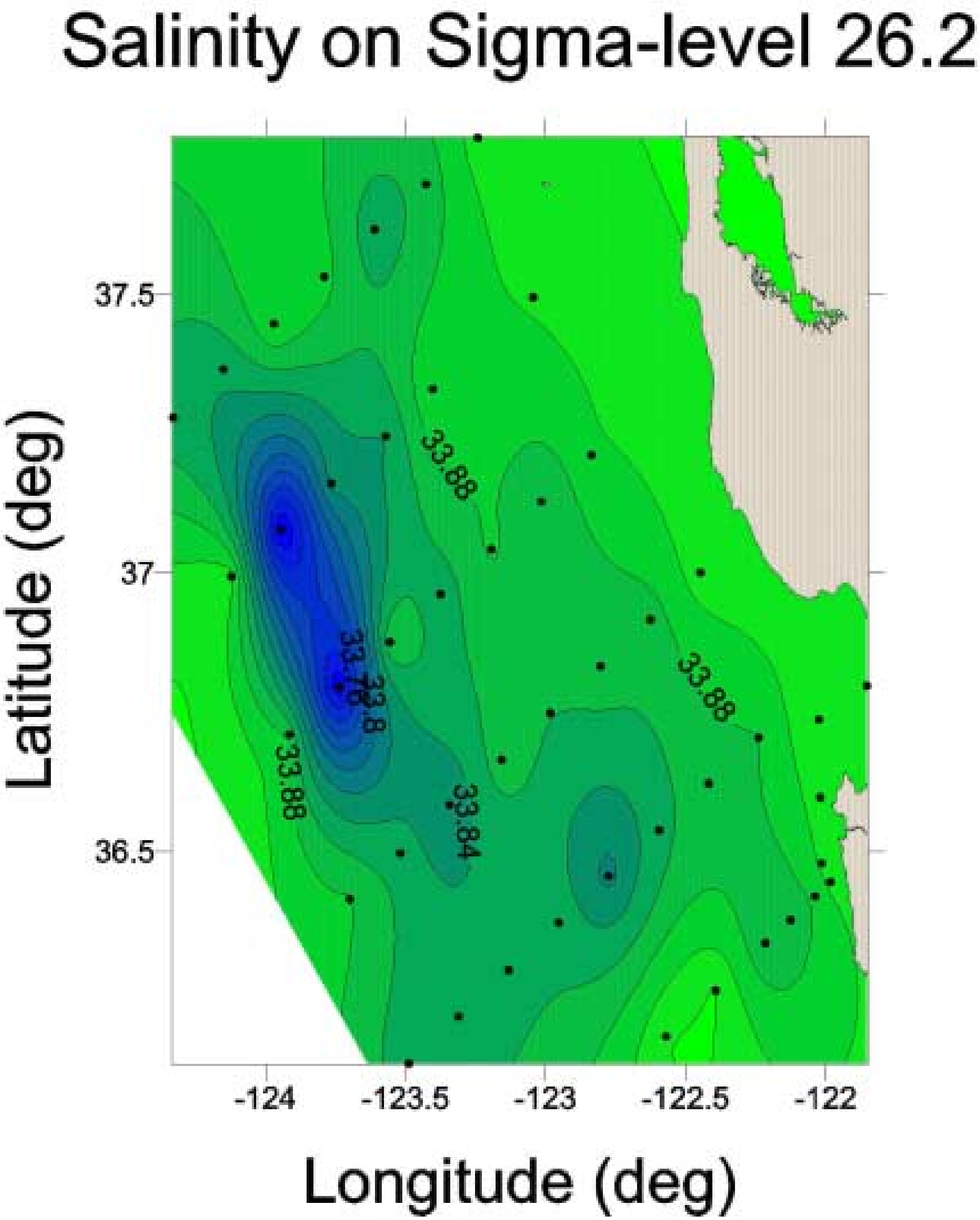
Pressure (dbar) on
Sigma-level 26.7
Latitude (deg)
37.6
37.4
37.2
37
36.8
36.6
36.4
36.2
-124
-123.5
-123
-122.5
Longitude (deg)
325
315
305
295
285

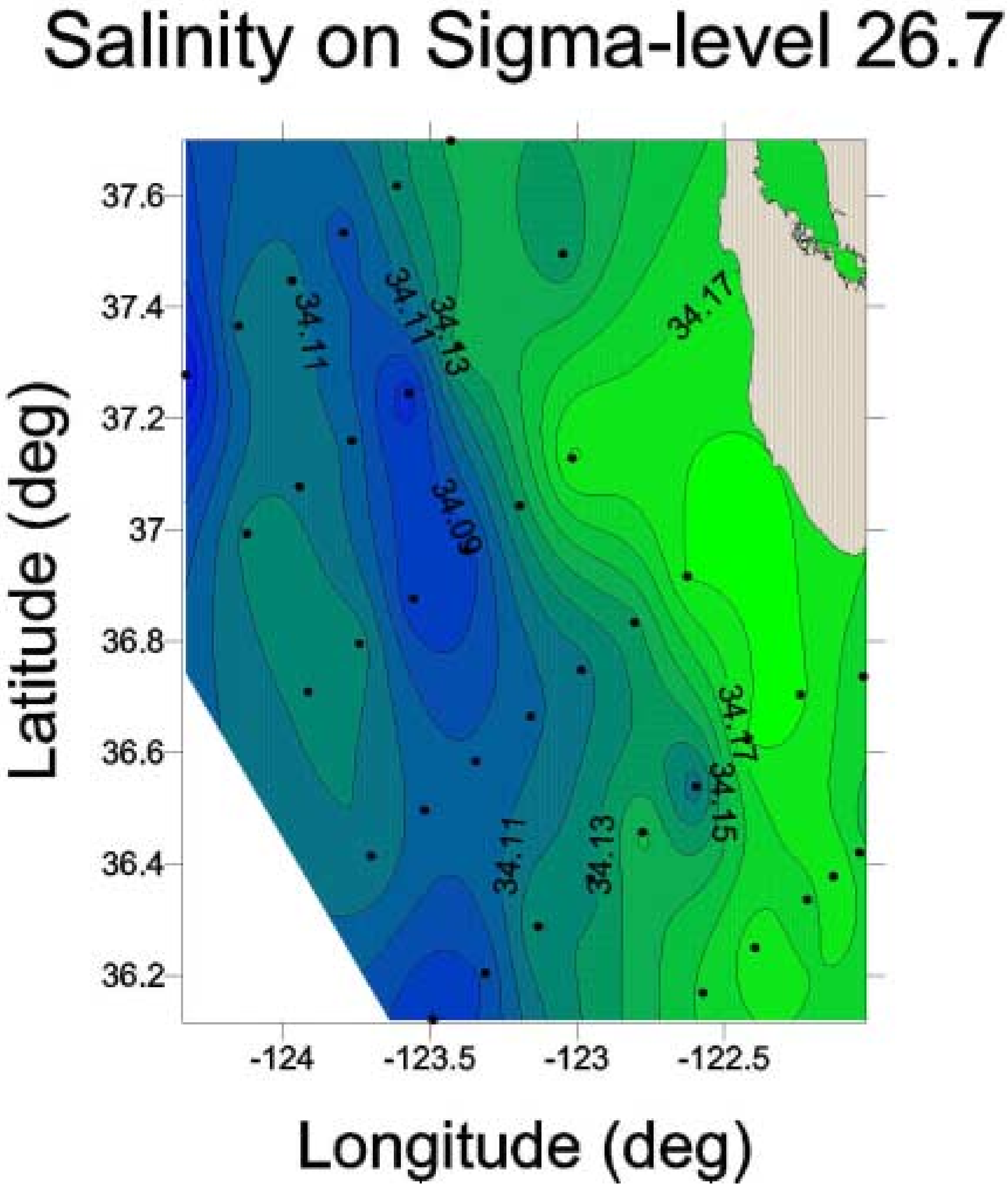


Density vs Salinity
−24.5
−25
−25.5
−26
−26.5
−27
−27.5
Density (kg/m3)
33
33.2
33.4
33.6
33.8
34
34.2
34.4
Salinity

Salinity on Sigma-Level - 25.8




Salinity on Sigma-level 26.2
37.5
37
36.5
-124
-123.5
-123
-122.5
-122
Latitude (deg)
Longitude (deg)
33.88
33.88
33.88
33.84
33.8
33.76



Salinity on Sigma-level 26.7
37.6
37.4
37.2
37
36.8
36.6
36.4
36.2
Latitude (deg)
-124
-123.5
-123
-122.5
Longitude (deg)
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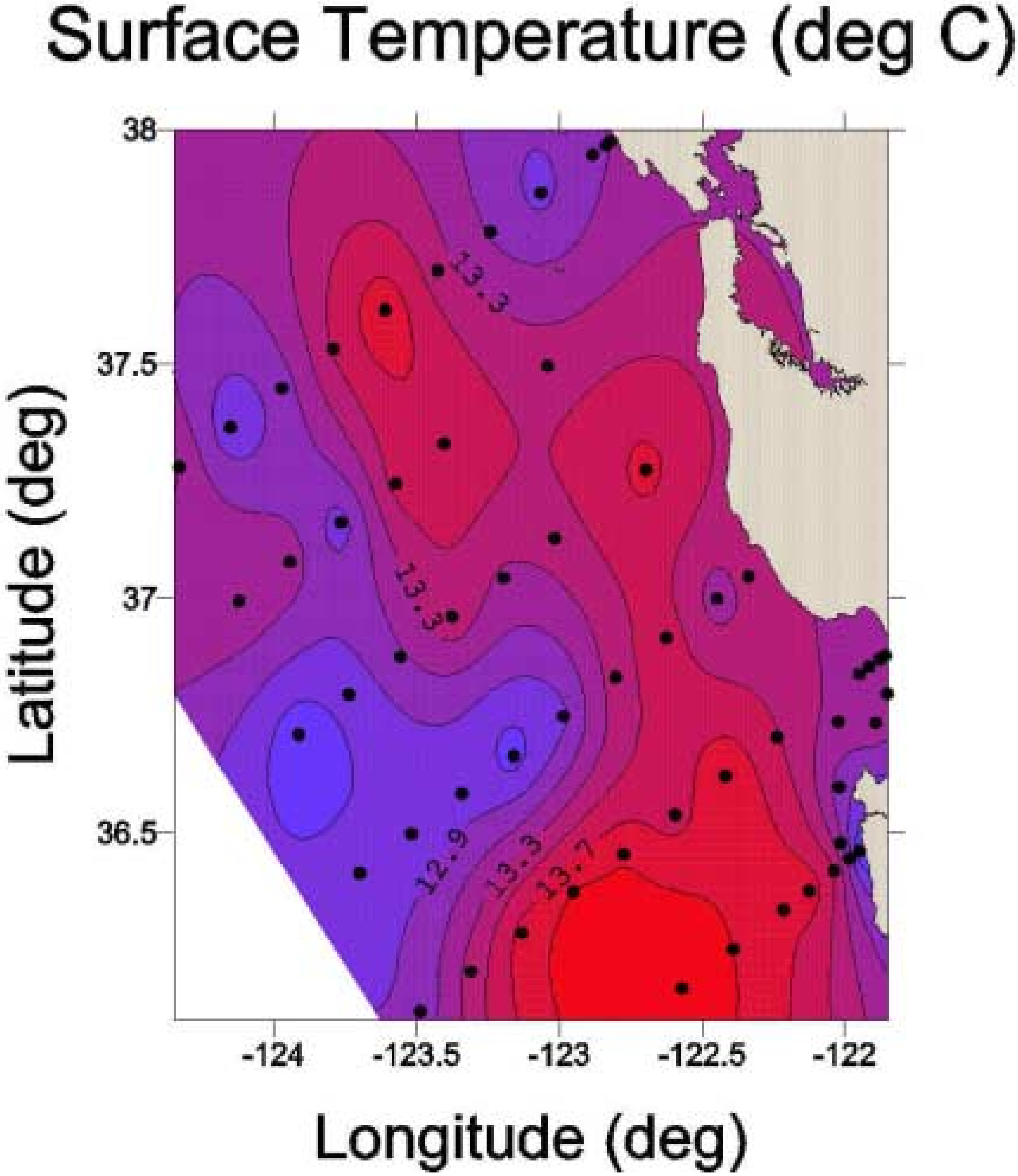
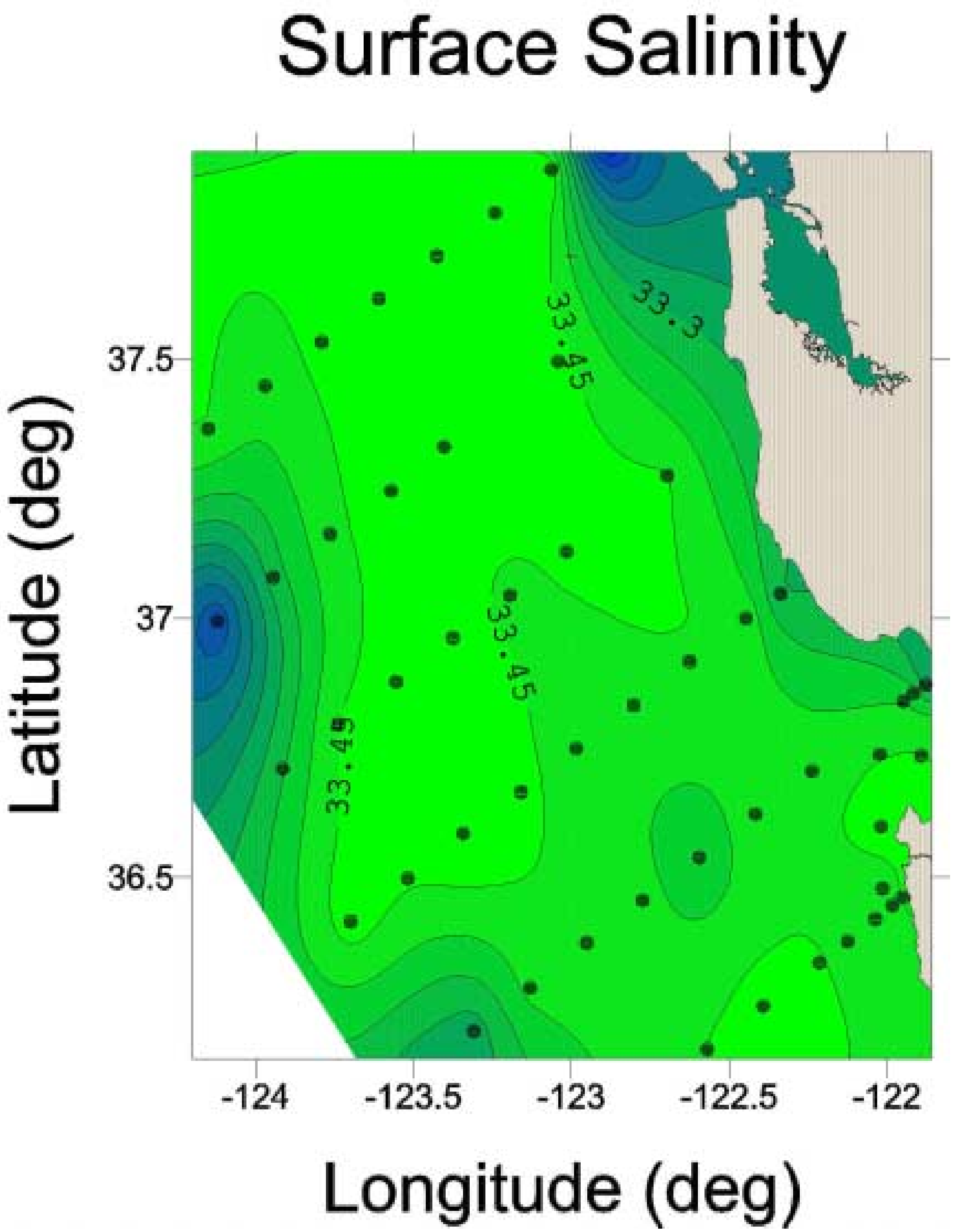
34.11
34.13
34.17
34.09
34.17
34.15
34.11
34.13


Surface Temperature (deg C)
38
37.5
37
36.5
-124
-123.5
-123
-122.5
-122
Latitude (deg)
Longitude (deg)
13.3
13.3
12.9
13.3
13.7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36.5
Latitude (deg)
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-123.5
-123
-122.5
-122
Longitude (deg)
33.45
33.3
33.45
33.45

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