OBSERVATIONS OF THE

INTERNAL TIDAL BORE

AT THE HEAD OF THE

MONTEREY SUBMARINE CANYON:

1-3 FEBURARY 2004

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TABLE OF CONTENTS

I. INTRODUCTION

A. BACKGROUND

1. Motivation

Graduate students studying the Operational Oceanography and Meteorology Course at the Naval Postgraduate School are required to plan and present a research project using oceanographic and meteorological field data. To complete this task, the class participated in a research cruise onboard R/V Pt Sur from 27 January to 3 February 2004. The cruise was divided into two legs. Leg I primarily concentrated on collecting data at numerous coastal stations between San Luis Obispo and Monterey Bay. While Leg II mainly collected data from within Monterey Bay itself. This report focuses on the analysis of data that was collected in the vicinity of the head of the Monterey Canyon, on 1-3 February 2003, during Leg II of the cruise. This data includes: a 25-hour time series and a 28-hour time series of conductivity, temperature and depth (CTD) profiles and Acoustic Doppler Current Profiler (ADCP) measurements.

2. Internal Waves and Internal Tides

Internal waves are can be generated by many mechanisms throughout the worlds oceans. One such mechanism is the interaction between flow and topography, an example being the interaction between the barotropic tidal currents and the continental shelf edge. The onshore tidal motions impinging on the continental shelf will acquire a vertical motion that may temporarily displace the pycnocline above its equilibrium position and then relaxation oscillations take place (Pond and Pickard 1983). The barotropic tidal flow thus induces a vertical, oscillatory displacement of the isopycnals situated above the shelf break. These disturbances then propagate away from the area of generation and form internal tides.

Internal tides and waves are wide spread phenomena at the continental shelf slope. The mixing and dissipation generated by internal waves have important effects on cross slope exchange processes and generation of the nepheloid layers (Key 1999). In addition, internal wave mixing may contribute significantly to ocean internal mixing. Hence the study of such phenomena is relevant to littoral warfare, in particular their effect on shallow water acoustic propagation and mine warfare operations.

3. Tidal Bores

A bore is an unsteady flow, often caused by tidal forcing and can be equated to a moving hydraulic jump (Lane –Serff et al. 2002). The most easily viewed tidal bore is seen propagating along the surface of a river, in the form of a breaking wave. This type of surface tidal bore occurs in some specific rivers, usually during exceptionally high tides. For this type of bore to form, the river exhibits certain characteristics; the banks form a converging funnel shape, the river bed gently rises, and the river is of considerable length. (Linden Software) A quite famous example of a tidal bore is the Araguari Pororoca, which occurs in the Amazon River in Brazil and can reach up to 6 meters in height.

Similar to the surface bore, is the internal tidal bore, which can exist in areas where a submarine canyon forms a converging funnel shape, combined with a gently rising sea floor, over a considerable distance. This type of topography causes an internal wave to become highly non-linear and steepen at its face, thus forming a bore. (Key 1999) The Monterey Canyon exhibits these particular topographical characteristics and is therefore an area of interest for the study of this phenomenon. (Petrunico et al. 1998)

B. PREVIOUS STUDIES

Many published studies have been previously conducted in the Monterey Canyon with the hope of describing the internal wave pattern and the internal tidal bores, which are evident at the head of the canyon. Previous work (Shepherd et al 1997, Shea and Broenkow 1982, Broekow and McKain 1972, etc..) is comprehensively reviewed in Petrunico et al. 1998 and Key 1999.

More recently, students undertaking previous operational meteorology and oceanography courses have done unpublished studies. (Watts 2003, Washkevich 2003) These studies both found evidence of an internal tidal bore at the head of the Monterey Canyon. However, Watts concluded the internal tidal bore was present in the form of a standing wave. Whereas Washkevich found the internal tidal bore to be in the form of a progressive wave.

C. PURPOSE

The purpose of this report is to analyse data collected from the aforementioned cruise on R/V Pt Sur to observe the processes operating at the head of the Monterey Canyon. More specifically, data analysis will be focused on finding evidence of the passage of an internal tidal bore and its classification as a progressive wave or a standing wave. This report is organised as follows: background information is given in section I. Data collection is described in section II. Data analysis and interpretation is presented in section III. Discussion of results and conclusions are given in sections IV and V respectively. The recommendations arising from the study are made in section VI. Finally, all figures are contained in section VII.

D. TOPOGRAPHY OF THE MONTEREY BAY CANYON

Monterey Canyon is located in the middle of Monterey Bay on the central Californian coast. Its upper reaches approach the coast to within a few hundred meters at Moss Landing, making it very attractive for deep-sea experiments and observations (Key 1999). Figure 1 shows the bathymetry of the Monterey Canyon with the two CTD stations and current meter mooring (TRBM) location marked. From the canyon head near Moss Landing, the submarine canyon then meanders offshore, roughly across the centre of Monterey Bay, in a generally cross-shore direction (080-260). Over a distance of 20 km, the canyon floor slopes from 1000 meters at the mouth of the bay, to approximately 100 meters at its head. (Watts 2003) The meandering of the canyon sees the axis of the canyon at time series 1 almost north east/south west, while at time series 2 location, the axis is almost east/west. The canyon is also much narrower inshore at time series 1 location.

II. DATA COLLECTION

A. SHIPBOARD

1. CTD

A 25-hour time series and a 28-hour time series of CTD casts were conducted in the vicinity of the head of the Monterey Canyon using the ship's Seabird CTD. For each time series, casts were conducted every hour and measurements were recorded every meter. In order to prevent accidental damage to the CTD equipment, a safety margin of approximately 10 meters between the CTD and the recorded bottom was used.

a) Time Series 1

The first time series centred on position 36^0 47.79' N, $121^0$49.25' W and data collection commenced at 0630 Pacific Standard time (PST) on 01 February and ended at 0730 PST on 02 February. Twenty-five CTD casts were conducted to a minimum depth of 160 m.

b) Time Series 2

The second time series centred on position 36^0 47.58' N, $121^0$50.54' W and data collection commenced at 0900 PST on 02 February and ended at 1316 PST on 03 February. Twenty-eight CTD casts were conducted to a minimum depth of 212 m.

2. ADCP

Throughout the CTD time series, measurements were also collected from the ship's onboard ADCP. The RD Instruments ADCP uses the Doppler affect to measure current velocity profiles. A short pulse of sound is transmitted at 150 kHz and the ADCP measures the change in pitch or frequency of the returning echo. The sound reflects off particles suspended in the water. These particles can be considered to be moving at the same speed as the water and hence, the ADCP ultimately measures the water velocity. As with all acoustic sensors, propagation loss limits the penetration of the ADCP in the water column. It was observed that the ADCP made reliable measurements to between 100 to 130 meters depth.

B. MOORED

1. TRAWL-RESISTANT BOTTOM-MOUNTED (TRBM) MOORING

One ADCP was deployed a on the trawl-resistant bottom-mounted mooring (here after referred to as TRBM), moored in shallow water, at the head of the Monterey Canyon as shown in Figure 1. This instrument was operational from 27 January to 3 February 2004 in position 36^0 50.4' N, 121^0 50.4' W. The TRBM uses the Doppler effect to measure current velocity and transmits a short pulse of sound, at a frequency of 2 MHz. The TRBM also has a pressure and temperature sensor. Unfortunately, the mooring flipped over at deployment; so there were no valid velocity data collected by the instrument. However, legitimate temperature and pressure records were retrieved from the TRBM.

C. TIDE GAUGE

Sea level data was obtained from tide gauge No. 9413450 located in Monterey Bay California and maintained by NOAA. The gauge measures changes in travel time of acoustic energy through a pipe within the gauge to infer sea level changes. The 6-minute mean sea level data recorded by this instrument was obtained from the NOAA website.

III. DATA ANALYSIS AND INTERPRETATION

A. IDENTIFICATION OF INTERNAL WAVES

1. Temperature and Salinity Measurements

As stated previously, the propagation of internal waves in the ocean and causes vertical motion within the water column. This vertical motion displaces water parcels from their equilibrium positions. Thus, evidence of the presence of internal waves can be gained from oscillatory displacement of the isopycnals, isotherms and isohalines within the Monterey Canyon. In order to study the vertical motions these tracers, CTD measurements of temperature and salinity were used to plot temperature and salinity profiles for time series 1 and 2. Figures 2a and 2b show temperature and salinity profiles for time series 1. Figures 3a and 3b display temperature and salinity profiles for time series 2. The internal wave motions can clearly be seen in each profile by the vertical oscillation of the isohaline and isotherms. The displacement of the isotherms and isohalines is greatest at depth and decreases towards the surface. These oscillations reached nearly 100 meters in the lower part of the water column.

Some phase lag relationships are evident between the signals at different depths in the water column. In both cases, the trough and ridges slope slightly with height. Thus illustrating the troughs and ridges arrive at different times at different depths in the water column. This observation indicates that the internal wave is in fact non-linear.

2. Density Calculations

Density was calculated from the temperature and salinity measurements using the formulae in Gill 1982. From these calculations the density profile for time series 1 and time series 2 is plotted and displayed as figures 4a and 4b respectively. Both these plots exhibit the same non-linear characteristics displayed in the temperature and salinity profiles. These figures also clearly show that the internal wave signal is semi-diurnal in character, experiencing to troughs and two ridges in a 24 hour period.

B. SEA LEVEL MEASUREMENTS

Sea level data from the Monterey tide gauge (9413450) was obtained and is plotted in Figure 5a. From this figure, it can be seen that Monterey Bay exhibited a mixed tidal cycle during this time period, exhibiting both diurnal and semi-diurnal constituents.

Figure 5b shows the bottom pressure variation as recorded by the TRBM for time series 1 (left panel) and time series 2 (right panel). Comparisons of figures 5a and 5b reveal that the TRBM bottom pressure plot was very similar to the Tide Gauge plot and showed the same pattern and height variations in sea level. As to be expected then this data can be equated to the variation in sea level and the tidal cycle. The Monterey tide gauge data has a resolution of 6 minutes so any small variations between the two data sets are negligible. As a result, the plot obtained from the TRBM, was used for comparisons between the mean sea level and observed changes in other quantities.

C. CURRENT MEASUREMENTS

The current data was divided into the normal u (east/west) and v (north/south) components, where a north component equates to a flow to the north and similarly for the other components. Figures 6a and 6b show the current component profiles for time series 1. Figures 7a and 7b show the current component profiles for time series 2. Due to the meandering of the canyon, this does not necessarily equate to along-canyon and across-canyon flow. At the canyon head time series 1 location, the axis of the canyon at time is aligned almost north east/south west and so strong current velocities were observed for both u and v components. While at time series 2 location the axis is almost east/west and hence the velocities were concentrated in the u component. For both time series it is evident that there is a current reversal in the top 40 meters of the water column.

Figure 8a and 8b show vector plots of the ADCP measured currents for time series 1 and 2 respectively. For time series 1, the currents are measured at 105m and for time series 2 were measured at 165 meters. These depths equate to the deepest depth of continuous measurements made by each instrument. Plots of bottom pressure are also included, in order to compare the observed changes in the currents with the tidal cycle. Although Figure 8a and 8b do not indicate a distinct pattern between the tide and the current velocities, the topographic steering of the canyon is evident. For time series 1, a northeastward up-canyon flow is evident of around 7-10 cm/s. While the down canyon current rotates to the south to southeast. For time series 2, a similar pattern was evident, except the currents were aligned more to the east-southeast/west-northwest, corresponding to the canyon axis at this location. In addition, the current velocity peaks at 5 cm/s, which was half that of the current velocity maximum for time series 1. This was attributed to the fact that the canyon at time series 1 was much shallower and narrower than at time series 2, thus funneling a faster flow velocity.

C. VELOCITY, TEMPERATURE AND SEA LEVEL COMPARISONS

Figures 9 and 10 are summaries of previous data for time series 1 and 2 respectively. These figures were constructed in order to view a comparison between the timing of the barotropic tide, the internal wave propagation and the variation in the surface and bottom currents. A plot of CTD temperature at 3 different depths in the water column and a depth average was used to simulate the up and downward displacement of the thermocline and the subsequent internal wave pattern. Both the east/west and the north/south velocity component of the ADCP data are shown for comparison in order to deduce internal wave propagation.

For time series 1, the strongest onshore flow currents exists at about 1500 PST and 0300 PST. Thus the velocities appear to be 90º out of phase with the semi-diurnal internal wave signal and show no correlation with the diurnal surface tidal signal. At around 1300 and 0100 PST, there is a distinct reversal of current direction, increase in velocity, as well as a steep temperature drop.

For time series 2, the strongest onshore flow currents also exist at about 1500 PST and 0300 PST. As for time series 1, the velocities appear to be 90º out of phase with the semi-diurnal internal wave signal and show no correlation with the diurnal surface tidal signal. At around 1300 and 0001 PST, there is a distinct reversal of direction, increase in velocity, as well as a steep temperature drop.

IV. DISCUSSION

A. IDENTIFICATION OF INTERNAL TIDAL BORE

The arrival of an internal tidal bore is characterised by wave steepening, a sharp drop in temperature over the water column, as well as a significant increase in upslope current velocity at the bottom. (Leichter 1996) From analysis of the results presented here, it is therefore consistent with the passing of internal tidal bores at around 1300 02 Feb, 0100 and 1300 02 Feb, and 0001 03 Feb. From figures 9 and 10, at these times, there are sharp drops in temperature characterised by the maximum upward displacement of the isotherms. Occurring at the same time are abrupt reversals in the bottom velocity data, from the south-westward (down-canyon) direction to north-eastward (up-canyon) direction for time series 1 and from the west northwest (down-canyon) direction to east-southeast (up-canyon) direction for time series 2. Figures 2-4 illustrate corresponding salinity and density changes. These changes in current direction are also clearly evident in the east/west ADCP velocity profiles in figures 6, 6b, 7a and 7b. The passage of the internal tidal bores is indicated in figures 9 and 10 by vertical black lines.

B. CLASSIFICATION OF INTERNAL TIDAL BORE

The passing of the internal bore should result in a strong up-canyon surge and the pumping of cooler, more saline waters from the canyon onto the adjacent continental shelf. (Pineda 1994) From figures 9 and 10, the bores occur during the beginning of the flood of the semi-diurnal internal tide. In addition, figures 9 and 10 shows that the bore velocities have their greatest intensities under the internal wave peaks and are most evident at the bottom where the walls of the canyon completely guide the water flow.

A standing wave is formed by the constructive interference of two waves, which travel in opposite directions in a medium. (Henderson2001) A wave is reflected from a barrier and there is a 180^0 change in the phase of the reflected wave. A model of a standing wave is shown in figure 11. Due to the interference of the two waves, there are certain points called nodes at which the total wave is zero at all times. The points at the middle between consecutive nodes are called anti-nodes. At the anti-nodes the total wave oscillates with maximum amplitude, equal to twice the amplitude of each wave. At these anti-nodes there is no horizontal velocity. Whilst at the nodes there is maximum horizontal velocity.

In the Monterey canyon it is considered that the head of the canyon acts like a barrier to reflect the waves and the maximum up-canyon/down-canyon velocity occurs half way between troughs and crest in the internal wave signal, analogous to nodes. The red vertical lines in figures 9 and 10 show these. From figure 11, the movement of water in the water column at internal wave crests and troughs (antinodes) would be primarily up and down. It is therefore considered that the bore acts to pump water upward and downward at the canyon head. (Watts 2003)

V. CONCLUSIONS

Firstly, from observations of data it is evident that the mechanisms for internal waves were operating during the two time series in which data was collected at the head of the Monterey Canyon. Secondly, the passage of internal tidal bores was evident from the collected data and they were observed in the form of standing waves.

A thorough understanding of the tidal bore phenomena cannot be obtained though this short study. Instead, more thorough research and a much longer time series of data are required. Indeed, the formation of internal bores in offshore submarine canyons is not fully understood and this study only scratches the surface of what is a very complex and intricate process.

VI. RECOMMENDATIONS

A. CURRENT DATASET

The current dataset could be enhanced through a more in depth statistical analysis of each time series. An example is to obtaining quantitative measures of phase difference between temperature, velocity time series and the internal wave signal.

B. FUTURE STUDY

In order to study the existence of tidal bores in the Monterey canyon, a more detailed study would need to be sought, more specifically one containing measurements of higher temporal and spatial resolution. An experiment that included simultaneous continuous density measurements at numerous stations along canyon axis, would give a better insight into the propagation and evolution of the tidal bores.

VII. FIGURES

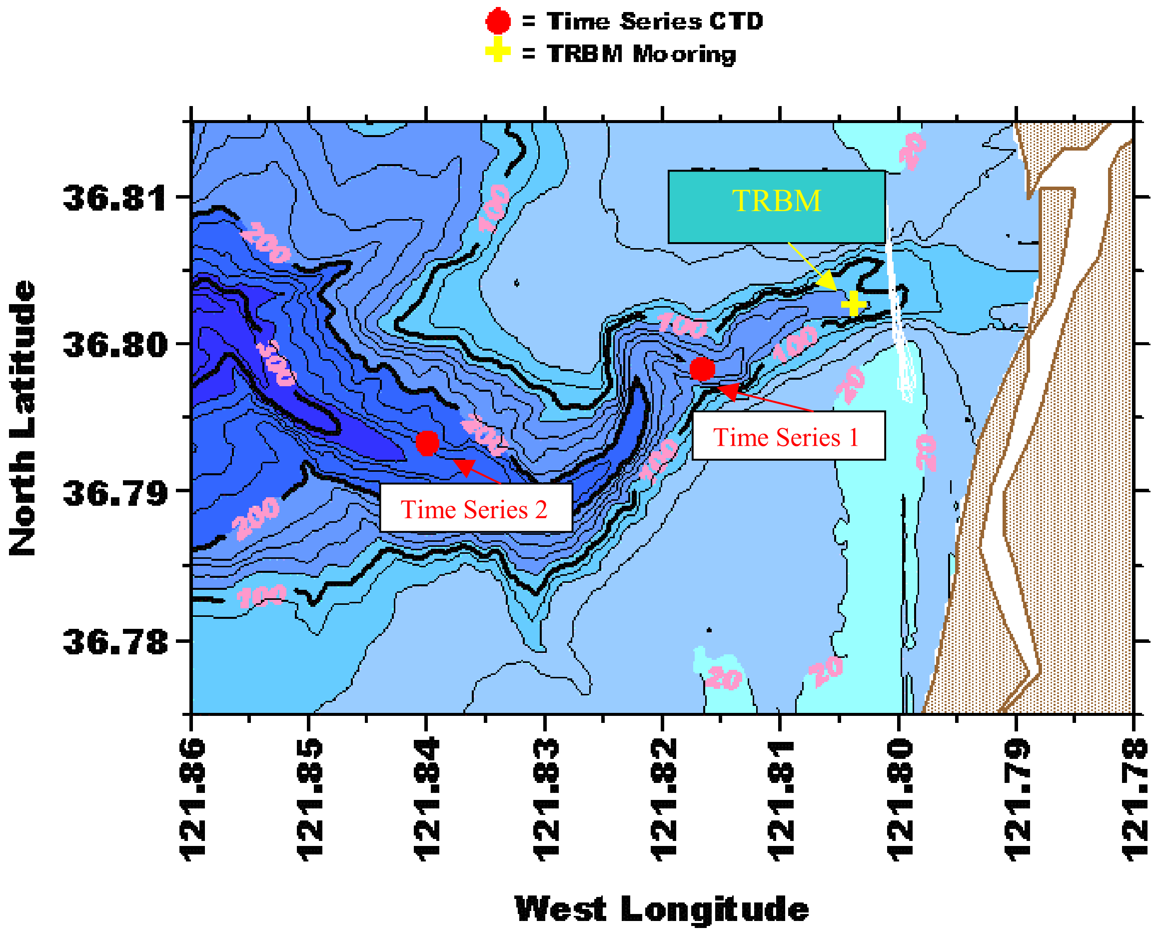

Figure 1: Location of Data Collection and Bathymetry at the head of the Monterey Canyon with the CTD stations and current meter moorings marked.

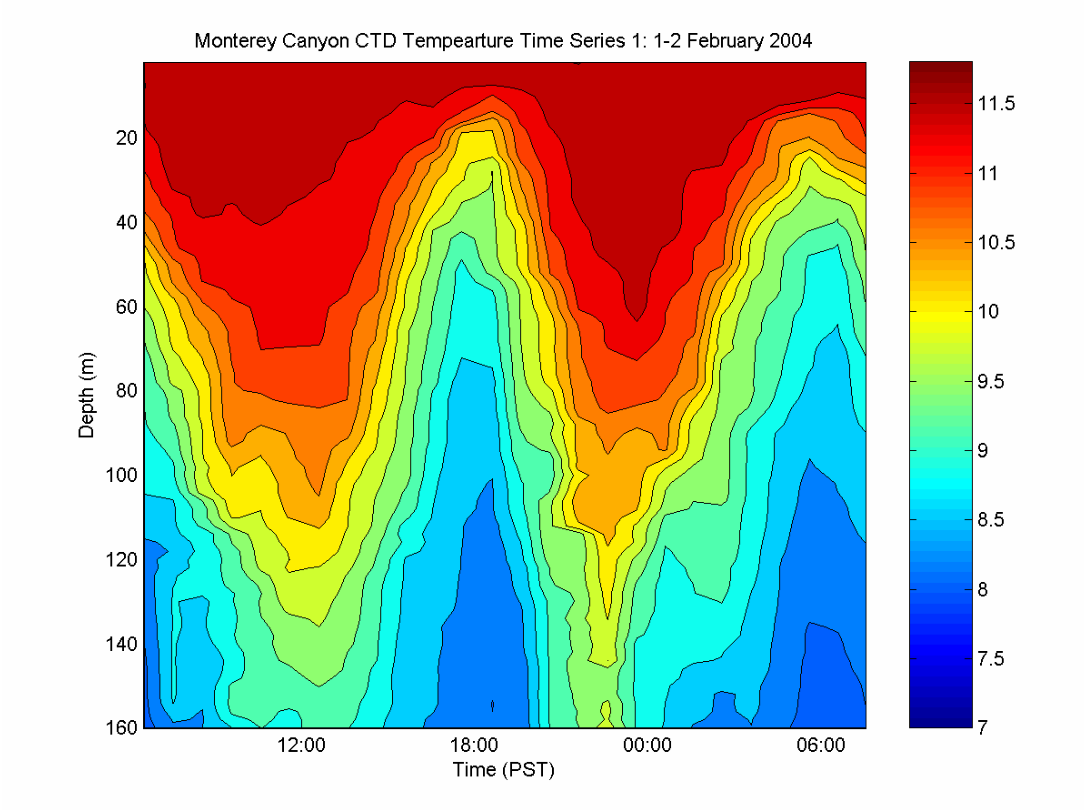

Figure 2a: **CTD Time Series 1 Temperature profile 1-2 February 2003.**

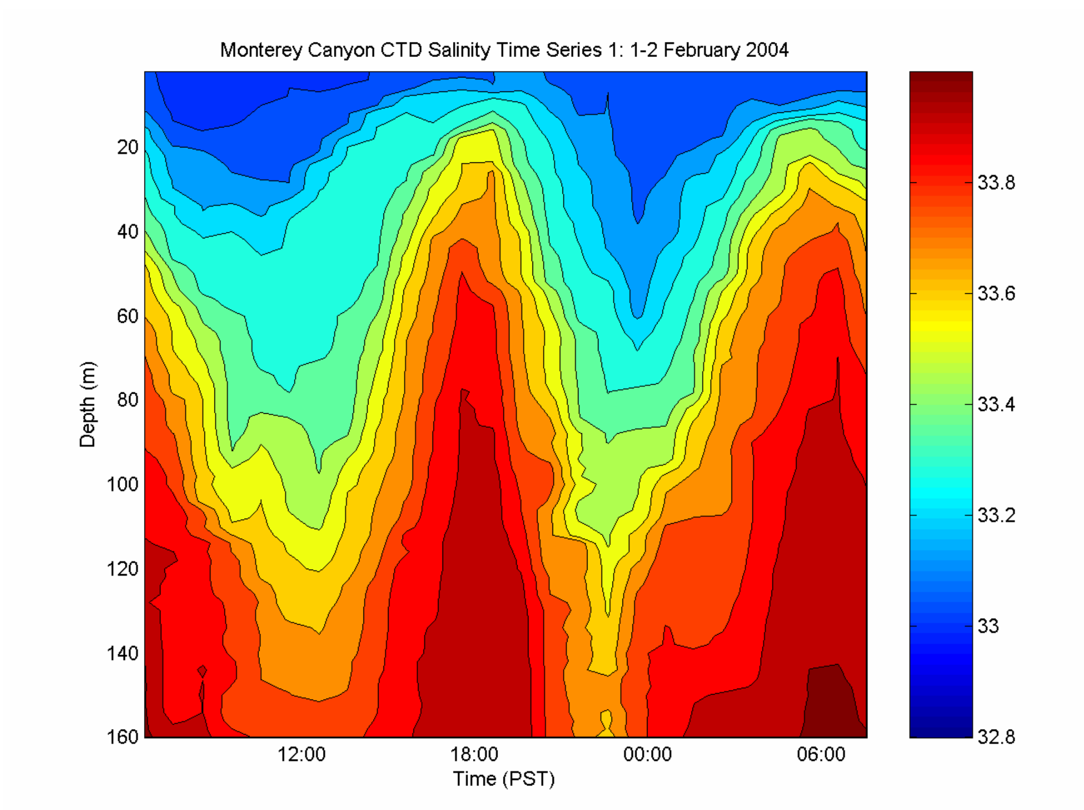

Figure 2b: **CTD Time Series 1 Salinity Profile 1-2 February 2003.**

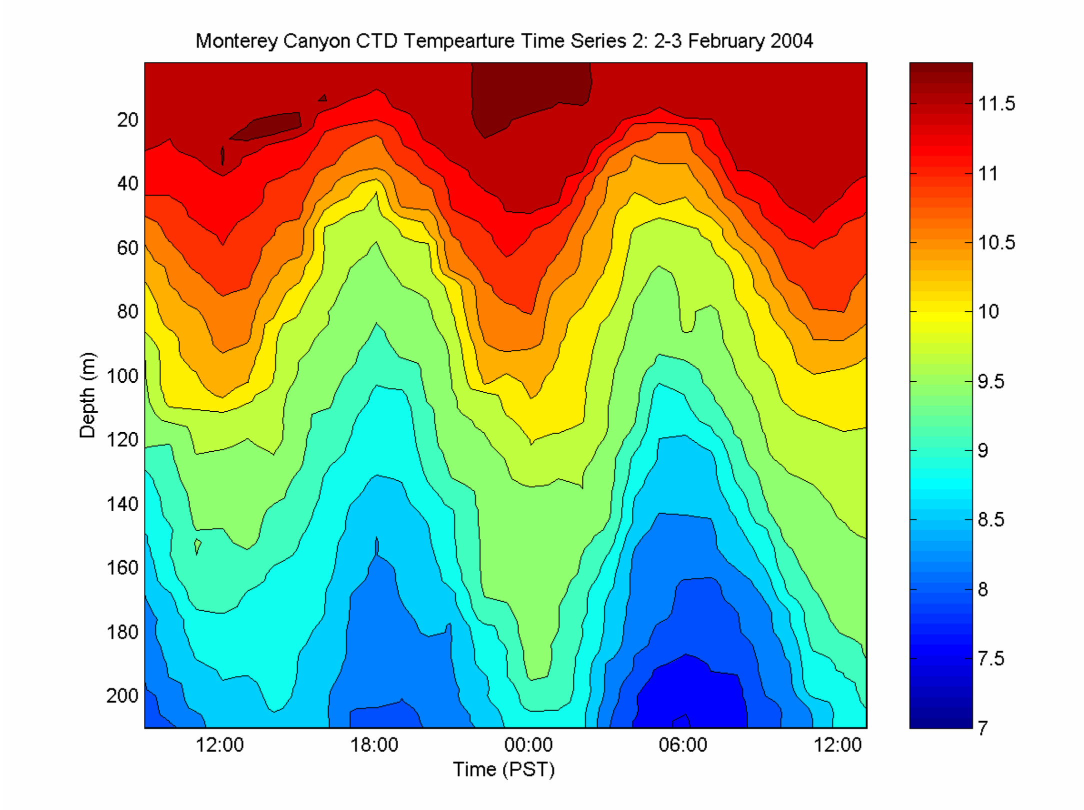

Figure 3a: **CTD Time Series 2 Temperature profile 2-3 February 2003.**

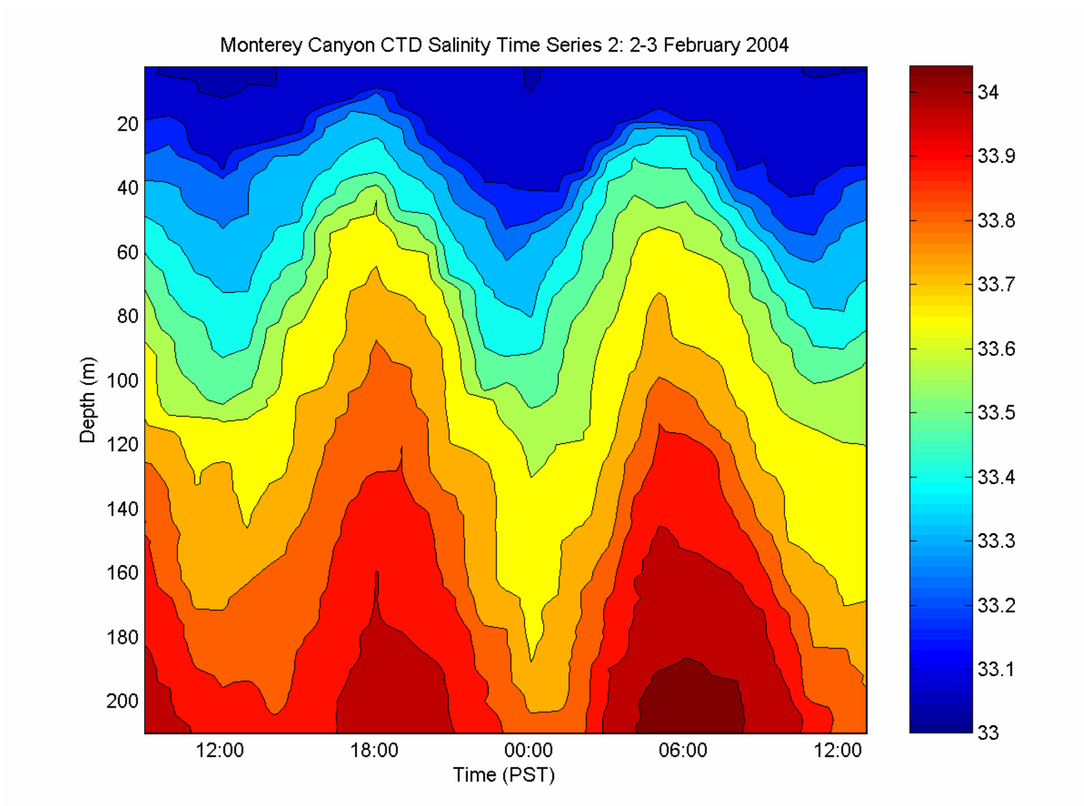

Figure 3b: **CTD Time Series 2 Salinity Profile 2-3 February 2003.**

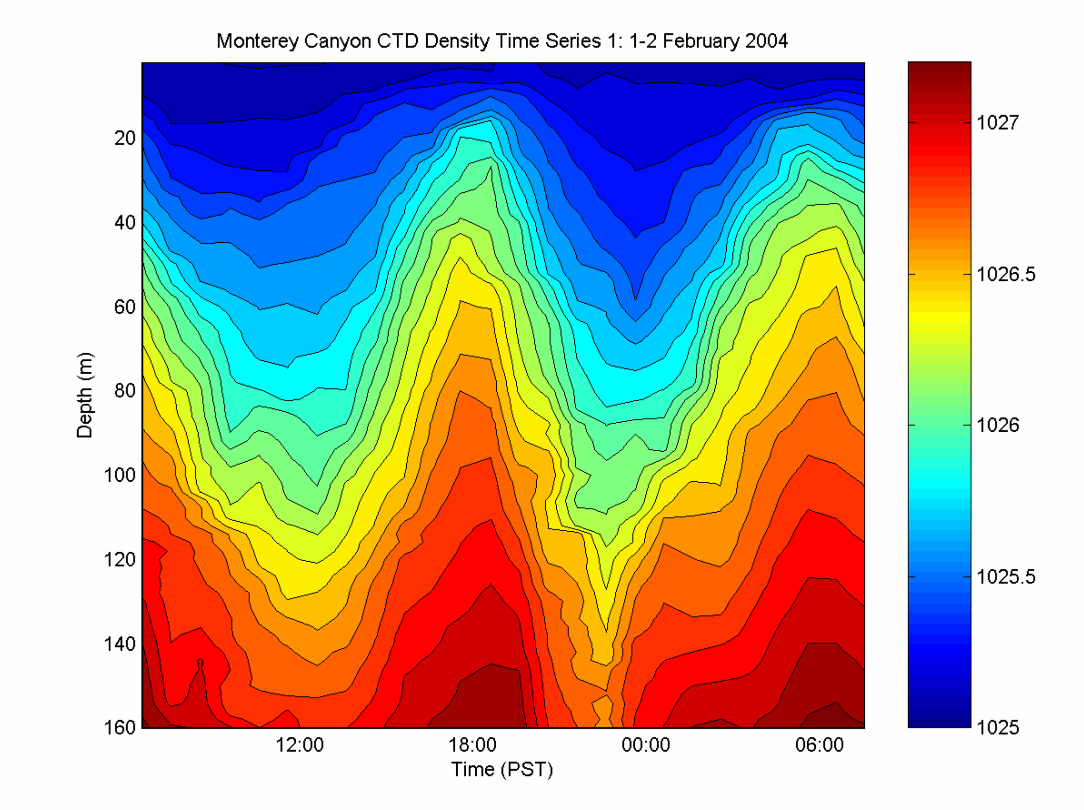

Figure 4a: CTD Time Series 1 Density Profile 1-2 February 2003.

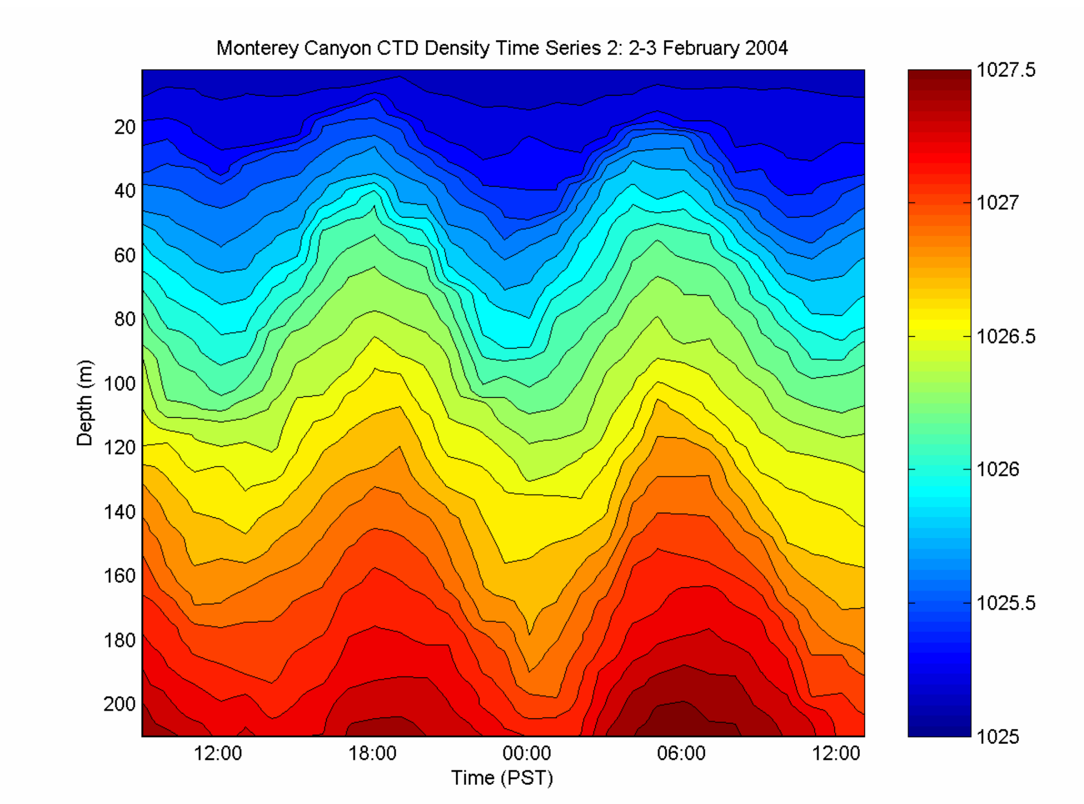

Figure 4b: CTD Time Series 2 Density Profile 2-3 February 2003.

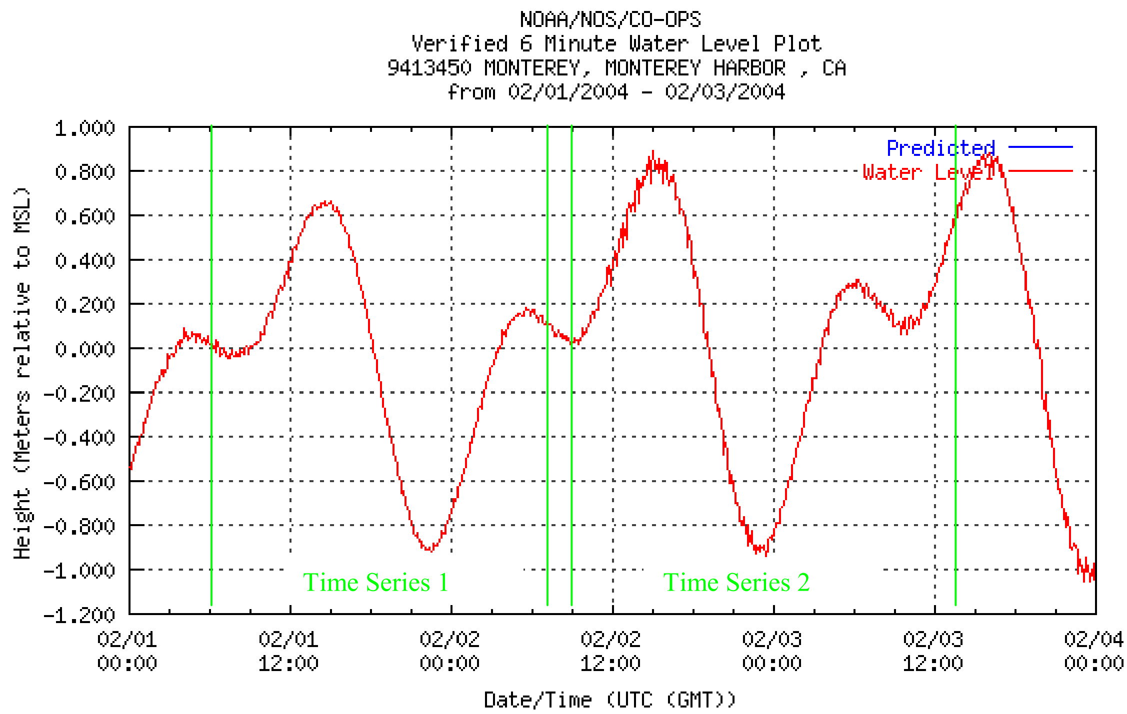

Figure 5a: **Observed 6-min MSL Monterey Tide Gauge 1-3 February 2003**

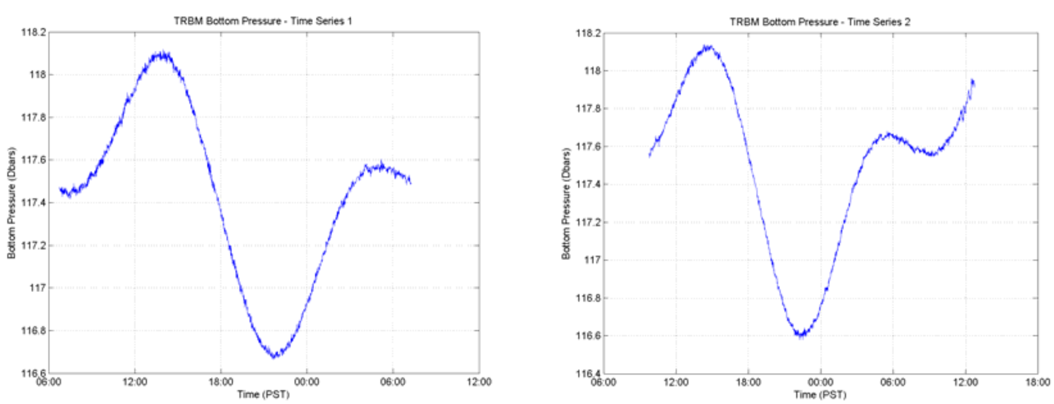

Figure 5b: **TRBM Bottom Pressure Observations Time Series 1 (left panel) and Time Series 2 (right panel)**

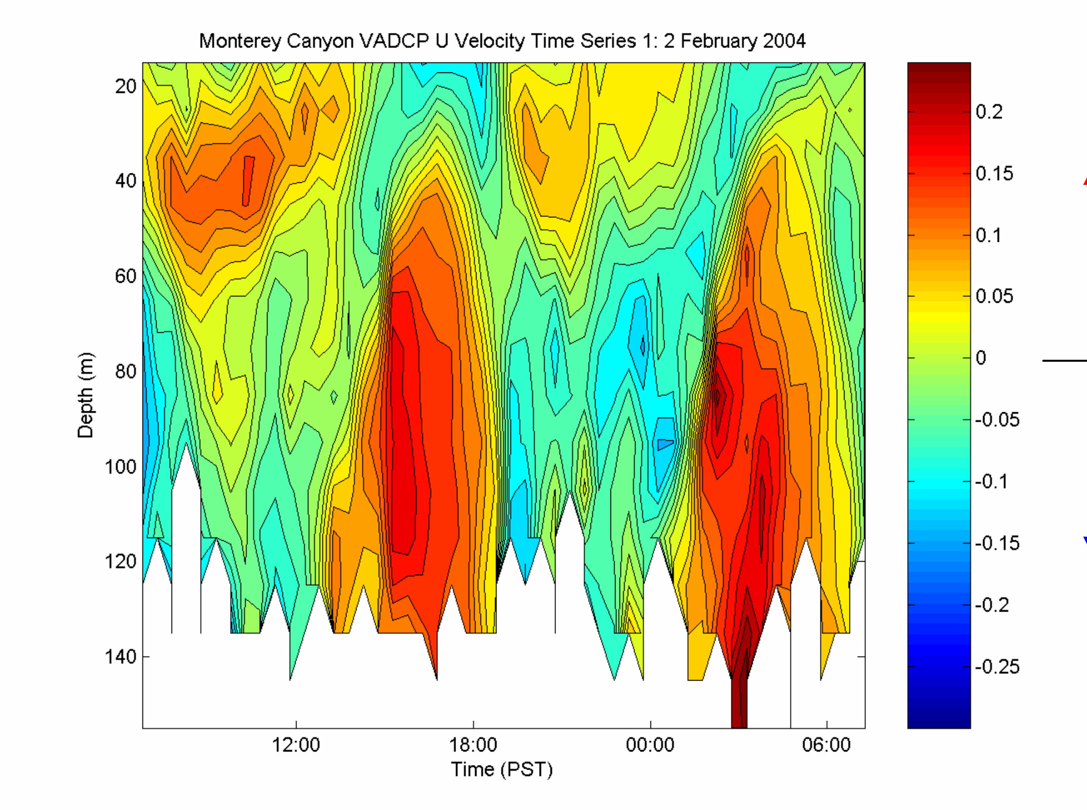

Figure 6a: **Time Series 1 VADCP U (East-West) Velocity 1-3 February 2003.**

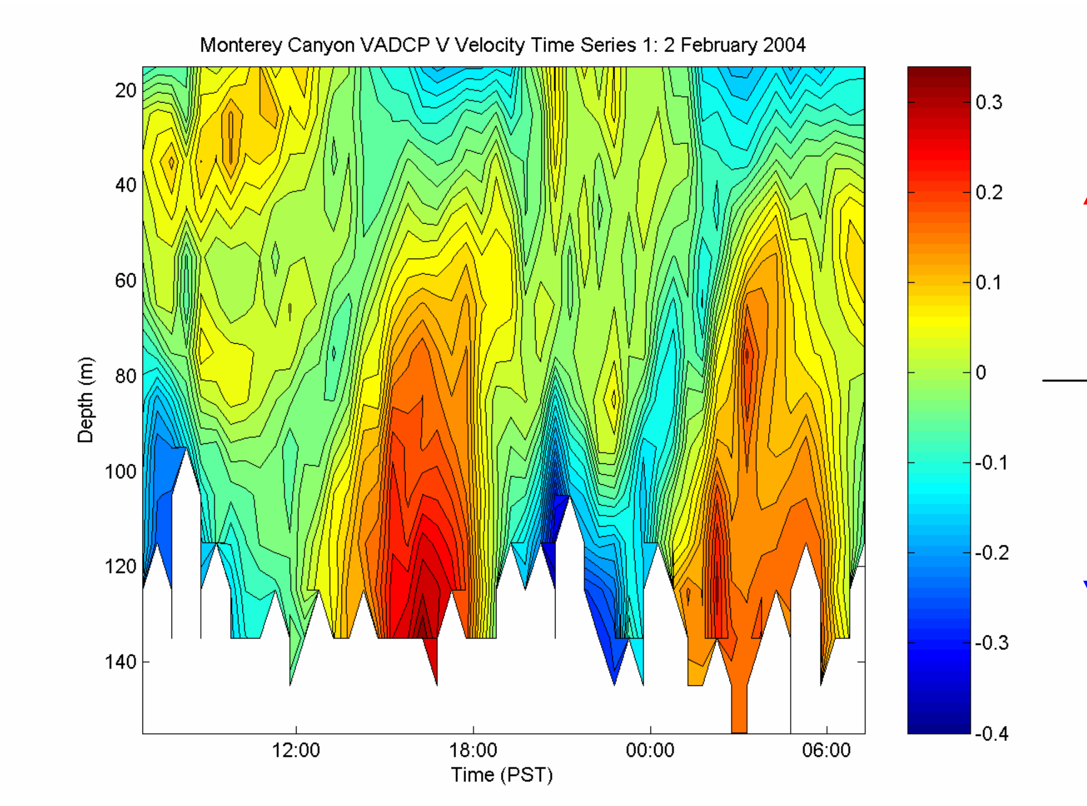

Figure 6b: **Time Series 1 VADCP V (North-South) Velocity 1-2 February 2003.**

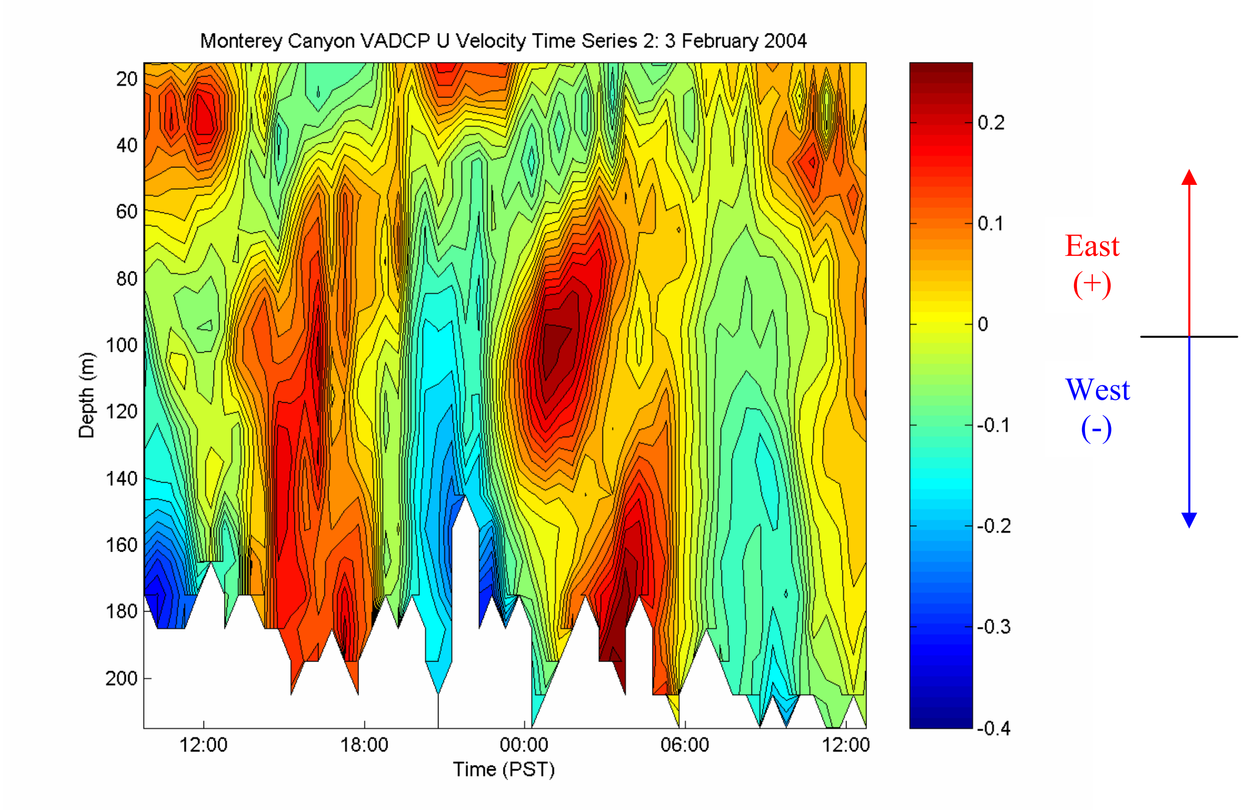

Figure 7a: Time Series 2 VADCP U (East-West) Velocity 2-3 February 2003.

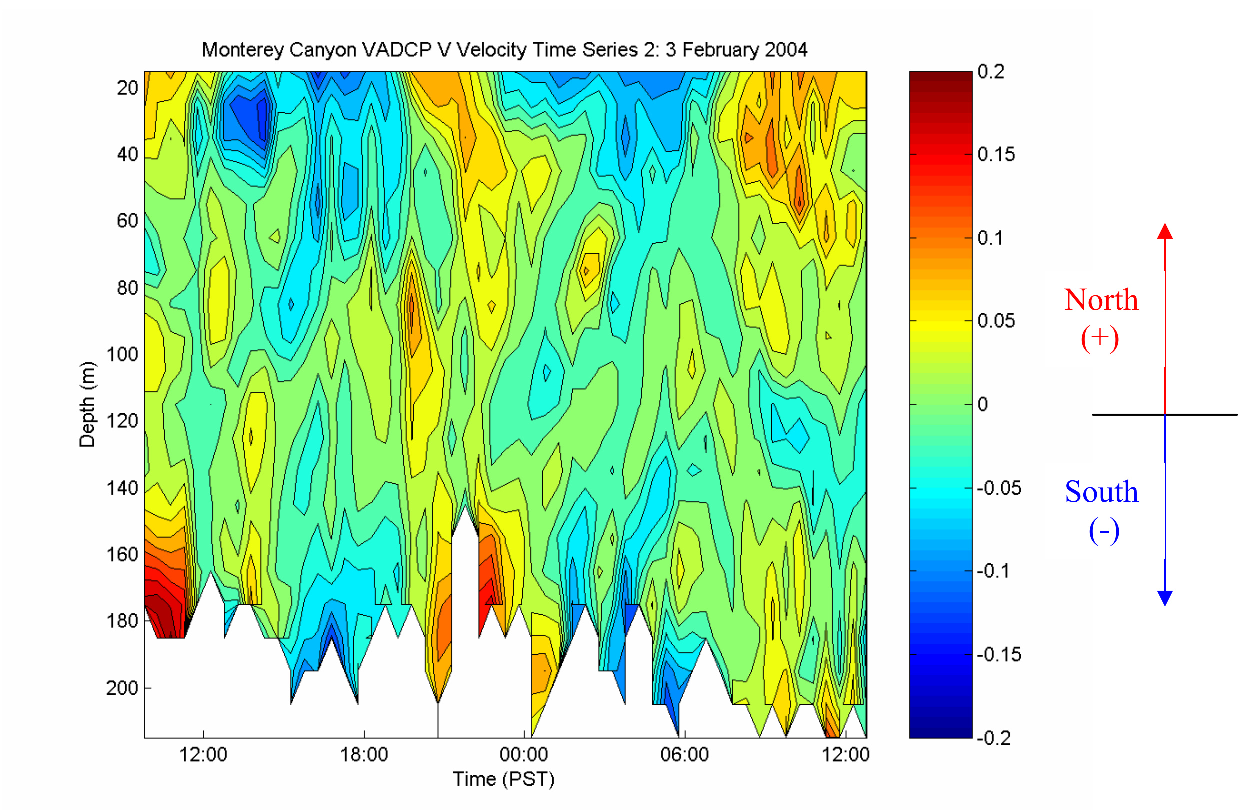

Figure 7b: Time Series 2 VADCP V (North-South) Velocity 2-3 February 2003.

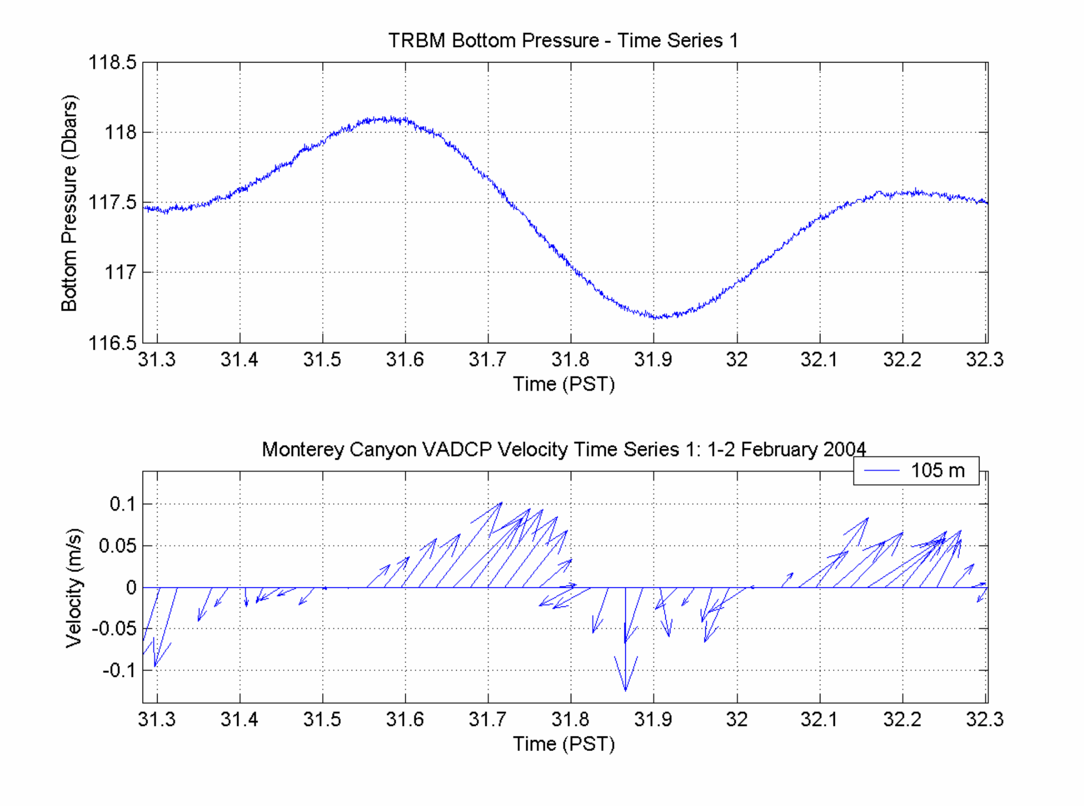

Figure 8a: Comparison of Bottom Pressure and Velocity at 105m - Time Series 1

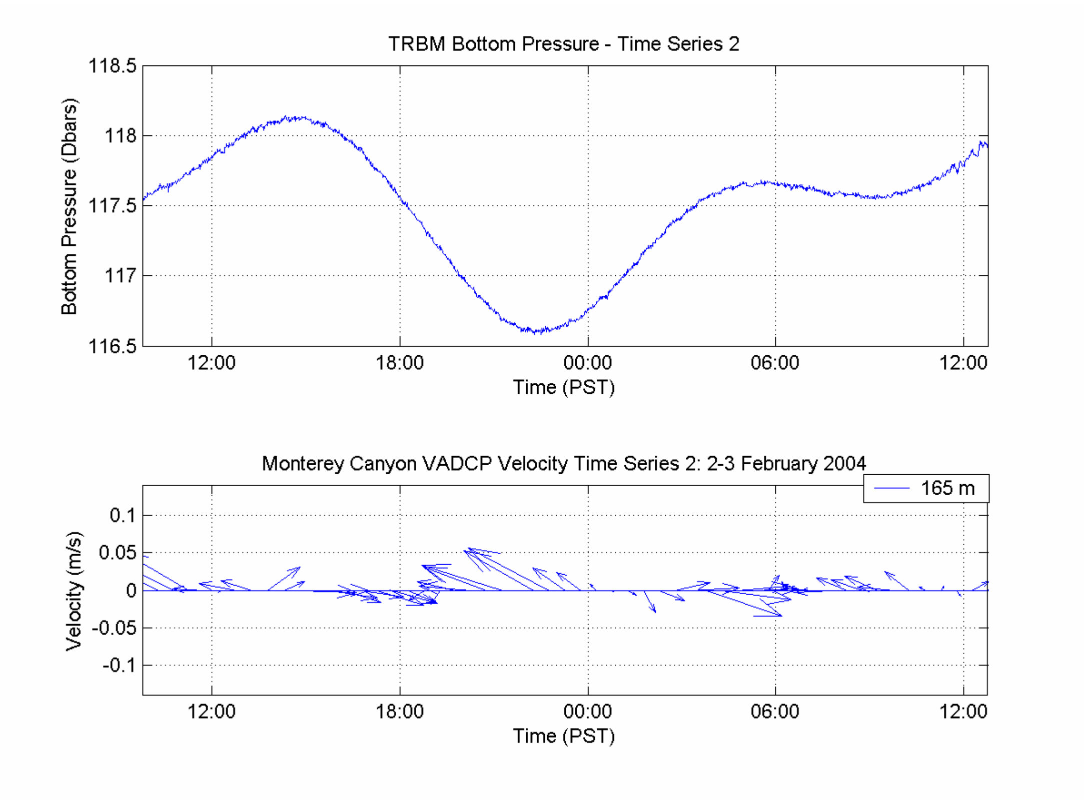

Figure 8a: Comparison of Bottom Pressure and Velocity at 165m - Time Series 2

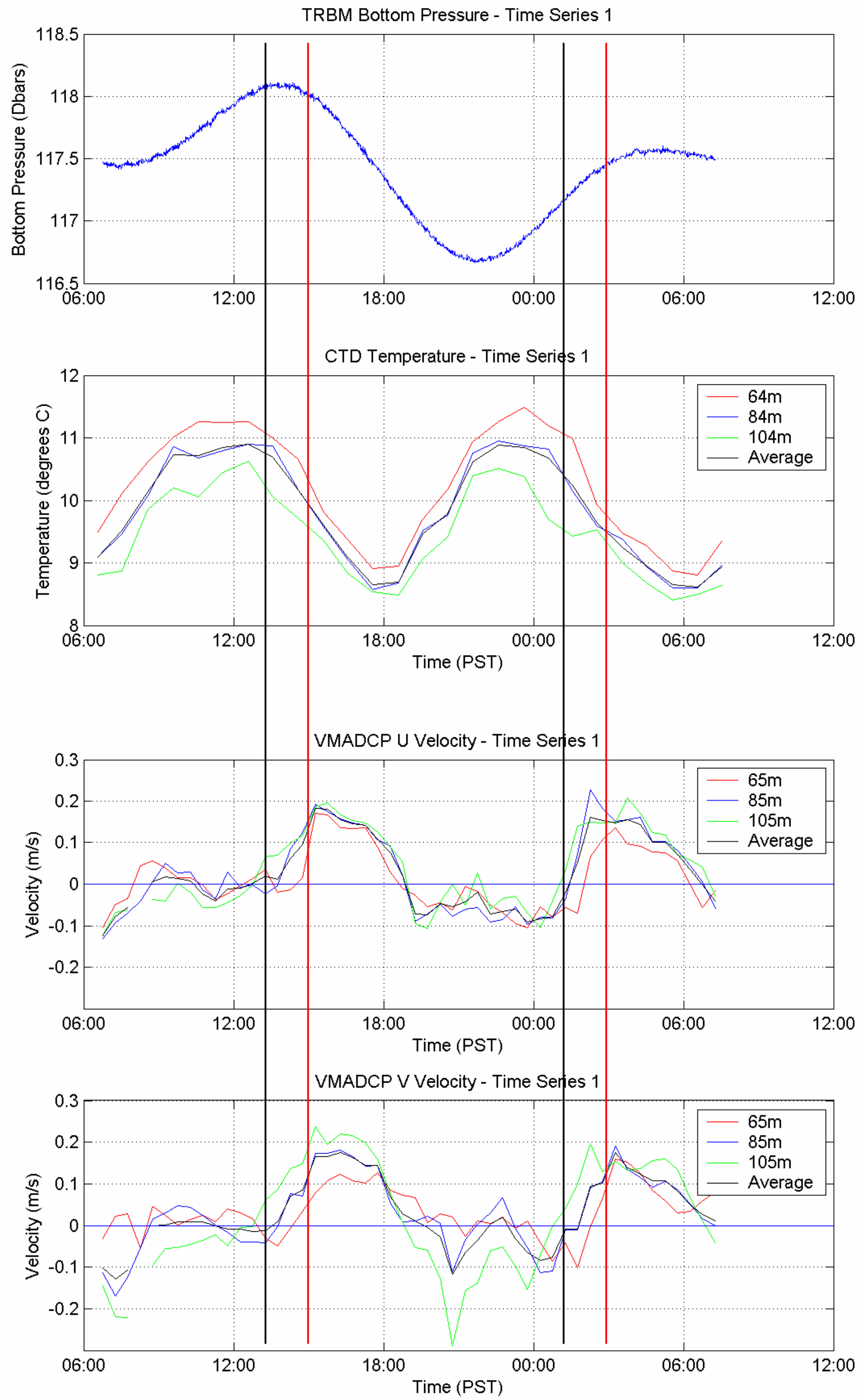

Figure 9: Comparison of U, V, Bottom Pressure and Temp. of Time Series 1 (black line indicates timing of the passage of the internal tidal bores, red line indicates up-canyon velocity maximum).

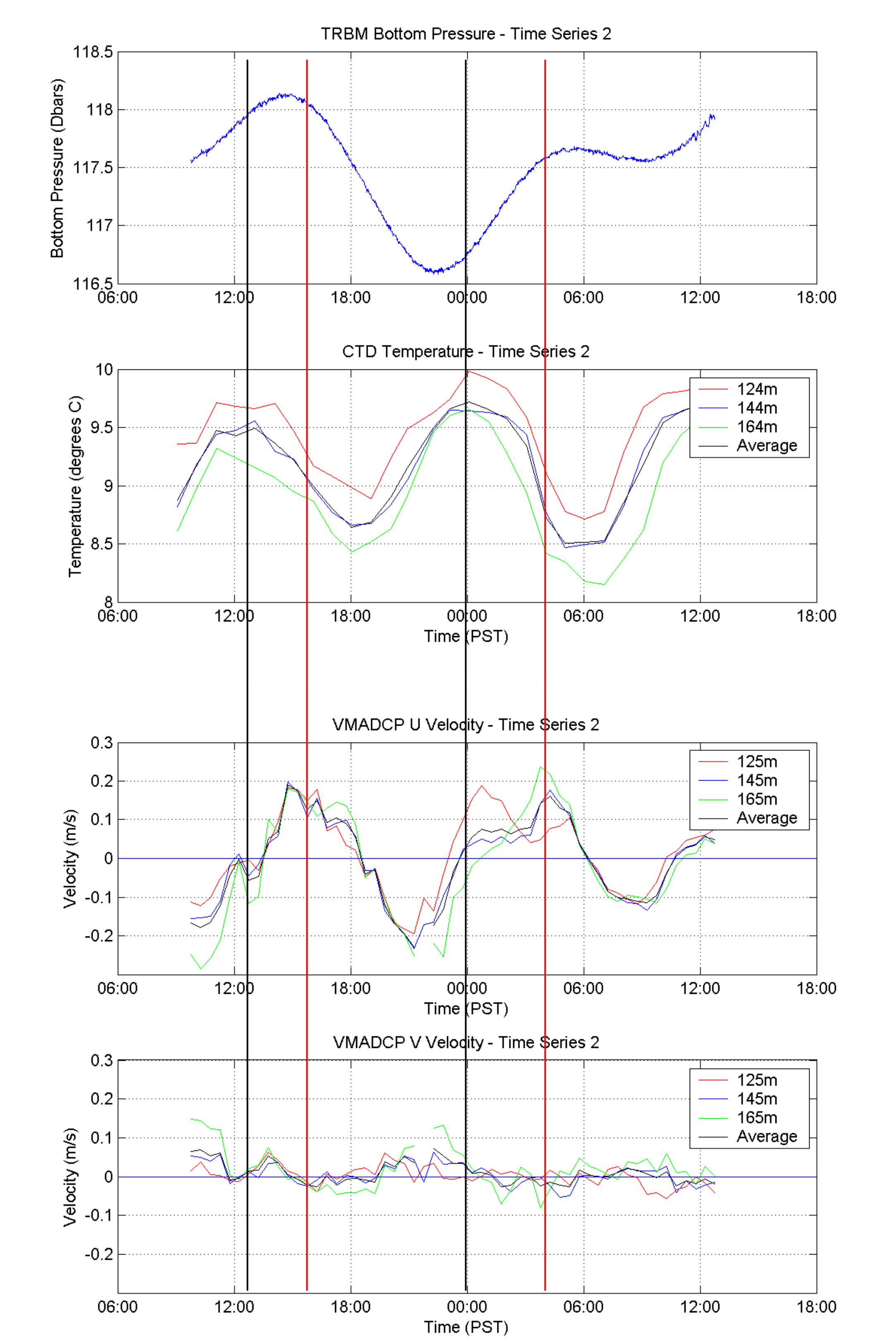

Figure 10: Comparison of U, V, Bottom Pressure and Temp. of Time Series 2 (black line indicates timing of the passage of the internal tidal bore, red line indicates up-canyon velocity maximum).

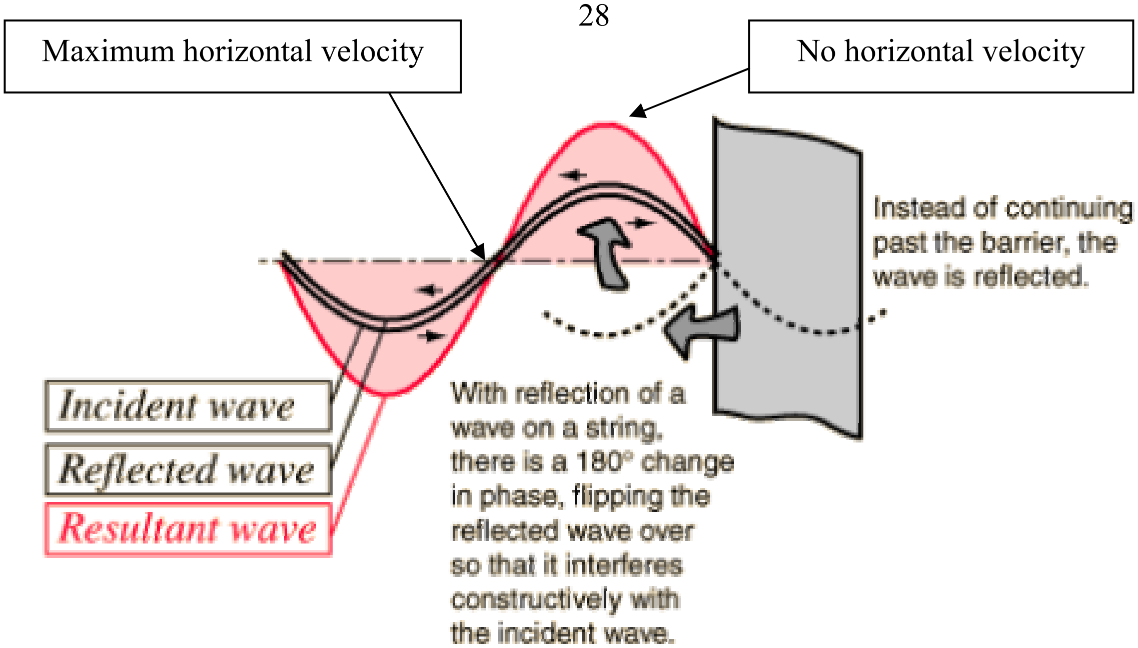

Figure 11: A standing wave. **(Adapted from Henderson 2001)**

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