Comparison of Buoy-Mounted 75-kHz Acoustic Doppler Current Profilers with Vector-Measuring Current Meters

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ABSTRACT

Long time series of atmospheric parameters and limited oceanographic parameters such as near-surface temperature and wave statistics have been available for some time. There is, however, a need for similar observations of currents in the coastal ocean. In December 1991, the National Data Buoy Center (NDBC) deployed two meteorological buoys in the Southern California Bight on a transect between San Diego and San Clemente Island. Each buoy consisted of a 10-m discus hull instrumented to measure a suite of meteorological parameters, and, for the first time in the NDBC buoy program, acoustic Doppler current profilers (ADCPs) were included to gather hourly current profiles beneath the two buoys. Moorings instrumented with seven vector-measuring current meters (VMCMs) were deployed adjacent to the NDBC buoys for several months and provided current observations for comparison with the ADCP measurements.

When the situation is such that the wave-induced buoy motion is not overly large, the observations of horizontal current made by the ADCP and the VMCM are highly correlated. Time series of differences between ADCP and VMCM measurements are characterized by a mean difference (bias error) of about 0.01 m s\(^{-1}\) and standard deviation of about 0.035 m s\(^{-1}\) for 1-h observations. Estimates of current spectra from ADCP and VMCM records suggest that the ADCP system can be characterized by a white noise level of \(2 \times 10^{-5}\) m\(^2\) s\(^{-2}\) (cph)\(^{-1}\). However, when the in situ environment is such that large surface waves are present (including breaking waves and whitecaps), erroneous current values are usually reported by the ADCP.

Mean values of vertical velocities reported by the ADCP appear to be much larger than what could be physically expected and are therefore deemed unreliable. As previously reported in the literature, the vertical velocities are contaminated by vertically migrating organisms and, while effective in detecting these diel migrations, the ADCP does not appear to yield useful observations of vertical water velocity in any of the frequency bands resolved by this set of observations.

1. Introduction

Since the early 1980s the Minerals Management Service (MMS) has provided funds to the National Data Buoy Center (NDBC) to maintain a network of meteorological buoys off the west coast of the United States. Observations from these and similar platforms supported by the National Oceanic and Atmospheric Administration (NOAA) and other agencies were used by Halliwell and Allen (1987) to describe the lower atmosphere over the northeastern Pacific over two summers and the intervening winter. They compared that description to geostrophic winds calculated from Fleet Numerical Oceanography Center atmospheric pressure analyses. While the numerical analyses captured essential features of the atmospheric circulation, details important in driving the coastal circulation were not resolved. Meteorological observations from the west coast buoy network constitute a unique dataset allowing long-term descriptions of the coastal wind field to be developed.

With the exception of sea surface temperature and sea level observations, comparable long-term observational records of physical parameters in the coastal ocean do not exist. With few exceptions, the longest time series of currents are of order two years, just sufficient to sketch the seasonal cycle, but inadequate to resolve interannual variability or long-term trends. In
1989 MMS requested that NDBC conduct an engineering feasibility study to determine how the buoys might be used as a platform from which long-term observations of current could be acquired using acoustic Doppler current profilers (ADCPs). ADCPs are well suited for such a task, because their design allows their operation for extended periods of time with minimal maintenance, and they are capable of providing current profiles to depths of several hundred meters. In 1991, MMS provided NDBC the funds to purchase three 75-kHz RD Instruments (RDI) narrowband ADCPs and to deploy two on 10-m-diameter discus buoys in the Southern California Bight (SCB). The two buoys were also to be equipped as well with the usual complement of NDBC meteorological and wave-measuring sensors. Moored nearby each buoy would be an array of vector-measuring current meters (VMCMs) to provide current observations against which the ADCP data could be compared.

A number of comparison experiments between moored ADCPs and conventional instruments using mechanical sensors have been reported in the literature. A 308-kHz profiler was moored in a bottom-mounted, upward-looking configuration on the northern California continental shelf for a period of 90 days in 133-m water depth (Pettigrew and Irish 1984). A surface mooring instrumented with VMCMs was deployed 300 m away. Comparison of current observations acquired from the two sets of instruments at different depths was excellent; vector correlations between pairs at similar depths exceeded 0.97 for the lower 100 m, and decreased to 0.94 near the surface. Mean and root-mean-square speed differences of 0.01 and 0.03 m s\(^{-1}\), respectively, were attributed to wave-induced contamination of the mechanical sensors and acoustic contamination of the acoustic sensors.

Magnell and Signorini (1986) described an extensive comparison of a bottom-mounted, high-resolution (1.2 MHz) ADCP with a variety of conventional moored current meters in a shallow (10 m), tidally forced domain. They found that the best agreement was between VMCMs and the ADCP, and that the ADCP "performed essentially as well as other good quality current meters, and significantly better than the nonvector-averaging instruments."

Johns (1988) reports on a comparison of an upward-looking 150-kHz ADCP moored 375 m beneath the surface in the Gulf Stream and an Aanderaa current meter moored 20 m beneath the ADCP. Over a 6-day period, the mean current difference was 0.01 m s\(^{-1}\) and the direction difference was 0.5°.

The goal of this comparison study was to obtain simultaneous observations using ADCPs and VMCMs at two sites, one more sheltered inside the SCB, and the other in a location farther offshore, with greater exposure to both winds and waves. The installation used in the present application, where the ADCP is mounted on a surface buoy that subjects the instrument to large fluctuations in pitch and roll as well as large vertical accelerations, was deemed sufficiently different from previously reported systems to warrant such a comparison with conventional current measuring devices.

2. The experiment

In 1991, a workshop convened by MMS to review available observations in the SCB recommended deployment of two NDBC buoys on a transect between San Diego and San Clemente Island (Fig. 1). In the SCB, forcing imposed by the atmosphere on the ocean becomes more vigorous with distance offshore. Observations of meteorological parameters are available for stations at San Diego and San Clemente Island. The NDBC buoys are identified by their World Meteorological Organization (WMO) station identifier. Buoy 46048, 30 miles off the coast, and buoy 46047, 60 miles west of San Clemente Island, sampled atmospheric and oceanic parameters over the ocean for about 18 months. The locations of the buoys are illustrated in Fig. 1 and listed in Table 1.

When the ADCP is deployed on a surface mooring, the pitch and roll motion of the platform on which the instrument is located causes the axis around which the acoustic beams are clustered to change its orientation from the vertical, and this motion could induce errors in the currents recorded in the instrument. To obtain relatively noise-free current estimates from individual Doppler-shifted returns, velocity estimates are commonly averaged over periods of several minutes, longer than periods characteristic of the surface gravity waves that move the surface buoy. While ADCPs have been used extensively on ships that are subject to significant rolling motion, their use on surface moorings, which are subject to more severe motion, raises questions about the significance of these motion-induced errors. The compass systems used in the ADCP systems function only at vertical tilt angles less than 20°, and large pitch and roll motions of the platform could thus affect the vector-averaging procedure.

To provide a standard for comparison, a single vertical array of seven VMCMs (Weller and Davis 1980) was moored close to each of the NDBC buoys. The VMCM has been used in many observational programs designed to study the response of the upper ocean to atmospheric forcing, and a substantial body of information exists concerning its performance (e.g., Beardsley 1987). The location of the VMCM moorings is listed in Table 1. At the offshore site, the distance between the two moorings was 2137 m, and at the inshore site the distance was 1651 m. While the total water depth at the inshore site was near 400 m for both moorings (Table 1), the water depth at the offshore site was different at each mooring, equal to 165 m for the
NDBC buoy and 311 m for the VMCM mooring, thus comparable measurements are available for only three depths offshore. The offshore site was an area characterized by abrupt changes in topography, and the final mooring locations came as a result of a compromise to keep the moorings as close as possible. The abrupt topography and different water depths may be responsible for some of the differences between ADCP and VMCM measurements observed at that site.

The ADCPs employed were the RDI narrow-beam 75-kHz model. The four acoustic transducers were separated from the electronic housing and located 1.3 m beneath the surface of the water. The ADCP transducer head subassembly was mounted in a well that penetrates the 10-m-diameter hull from the deck to the bottom to permit replacement at sea, as illustrated in Fig. 2. The electronic subassembly (in its watertight housing) was installed inside the buoy’s hull. A multiconductor cable, 10 m long, interconnected both subassemblies. The instrument measures current at regular intervals along each of four acoustic beams oriented at 90° intervals. The beams from each of the four acoustic transducers are tilted 30° from the vertical when the buoy is horizontal, so that three orthogonal components of the velocity can be deduced: eastward, northward, and vertical. The vertical velocity estimates used in this study were found from the ping-by-ping averages of the two vertical velocity measurements, each derived from a pair of oppositely oriented transducers. The average difference between the two vertical velocity measurements is termed the “error velocity.” “Echo level” from each of the four beams was also estimated and is defined as a measure of the signal strength of the returning echo. The units are decibels.

<table>
<thead>
<tr>
<th>Mooring</th>
<th>Latitude (N)</th>
<th>Longitude (W)</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADCP inshore</td>
<td>32°53.83'</td>
<td>117°52.46'</td>
<td>415</td>
</tr>
<tr>
<td>VMCM inshore</td>
<td>32°53.68'</td>
<td>117°53.34'</td>
<td>442</td>
</tr>
<tr>
<td>ADCP offshore</td>
<td>32°41.18'</td>
<td>119°35.35'</td>
<td>165</td>
</tr>
<tr>
<td>VMCM offshore</td>
<td>32°42.05'</td>
<td>119°36.11'</td>
<td>311</td>
</tr>
</tbody>
</table>

TABLE 1. Position and depth of ADCP and VMCM moorings.

![Fig. 1. Location of buoys deployed in the experiment.](image-url)
\[ \sigma = 1.6 \frac{10^5}{F L B P^{1/2}}, \]

where \( \sigma \) is the precision (m s\(^{-1}\)), \( F \) is the ADCP acoustic frequency (76 800 Hz), \( L \) is the depth cell length (16 m), \( B \) is the beam angle coefficient (=1 for 30°), and \( P \) is the number of pings per ensemble (170).

No ADCP tilt sensor was used based on the recommendations of the manufacturer and other considerations by NDBC. The RDI tilt sensor is best used for quasistatic angular measurement. It was believed that significant wave forcing would introduce spurious signals into the tilt sensor.

The flux-gate compass used by the RDI ADCP instrument is normally located on the acoustic transducer head. When this normal configuration was tested in the canal at the NDBC facility using a mock-up 10-m discus steel buoy, it was determined that compass deviation errors as large as ±80° occurred. The magnetic compass was relocated to the top of the buoy mast. The proper placement of a Flinders bar adjacent to the compass and further testing and adjustment reduced the compass deviation error to values no greater than ±3°.

The VMCM moorings are illustrated in Fig. 3. Surface buoyancy was provided by a 1.7-m spherical float. A 2-m-high tower was equipped with a radar reflector and a navigation light and also supported an Argos transmitter. The VMCM was designed to reduce errors in the sample average currents introduced by short-period motions—for example, by surface gravity waves. These instruments measure two orthogonal components of the horizontal current by means of two pairs of propellers mounted on perpendicular axes. The orientation of the VMCM relative to magnetic north is measured by means of a flux-gate compass similar to the one used in the ADCP. Velocity components are sampled every second and vector averaged over a period of 4 min. The VMCMs were also instrumented to measure temperature.

3. Horizontal velocities

a. Observations and data quality

Time series of the north component of current measured 56 m beneath the surface by the ADCP and by the VMCM are illustrated in Fig. 4, along with the time series of the difference between these observations. This data segment is characteristic of a large number of similar segments examined. In general, the major fluctuations in the current field are reproduced in the time series of each instrument, although the ADCP observations are characterized by larger fluctuations at high frequencies (periods shorter than 6 h), and these are reflected in the difference time series. The standard deviation of the various difference time series is of order 0.03 m s\(^{-1}\). After 1200 UTC 5 January, a large dis-
crepancy exists between ADCP and VMCM current observations. As this event is present in ADCP observations at all depths, but not seen in VMCM measurements at any depth, it is assumed to correspond to an error in the ADCP measurement system. Time series of the vertical velocity and of the error velocity reported by the ADCP for the same period of time are illustrated in Fig. 5. While the event just described is clearly evident in the vertical velocity, it is not apparent in the error velocity (the difference between two independent computations of the vertical velocity). In this instance the vertical velocity is a better indicator of corrupt data than the error velocity if, as we believe, this incident corresponds to an error of the ADCP system.

There were several short periods of rapidly changing horizontal and vertical current measurements in the ADCP records, as illustrated in Figs. 4 and 5. Such periods corresponded to periods of high sea state and wind speeds greater than 8 m s\(^{-1}\). Two characteristic episodes are illustrated in Figs. 6 and 7, where time series of wind speed and wave characteristics are compared to ADCP and VMCM current measurements and a typical echo level. Questionable ADCP measurements occurred at the outer buoy on 19 December 1991 (Julian day 353, Fig. 6), when the significant wave height increased steadily to a maximum of 4.8 m at 2100 UTC. During this period of high seas, the echo levels from each beam were lower than normal, probably due to loss of acoustic energy by bubble effects. The absolute value of the northward component of the current was notably large. From 1800 to 1900 UTC the hourly measurements at 56-m depth changed from \(-0.03\) to \(-0.435\) m s\(^{-1}\). The differences between the VMCM measurements and the corresponding ADCP measurements at that depth were also large: at 1400 UTC the difference was \(-0.333\) m s\(^{-1}\). The vertical velocity measurements exceeded \(-0.5\) m s\(^{-1}\) and approached \(-1\) m s\(^{-1}\) at several depths during this time period. These vertical velocity measurements indicate that the horizontal currents were contaminated by buoy motions or some other phenomenon rather than being unusual, but real, current events. On 5 January 1992 (Fig. 7) similar fluctuations in horizontal and vertical current measurements occurred at the inner buoy. On this occasion the significant wave height was less than 2 m, but the winds were increasing. Figure 7 reveals that at 104-m depth, the onset of the greatest hourly changes in current and the greatest differences between the VMCM and ADCP measurements occurred just after 0600, after wind speed began to exceed 8 m s\(^{-1}\).

These errors in horizontal current measurements are greater than expected. Regier (1982) points out that ‘the high correlation between the vertical velocity and the slope of the sea surface . . . leads to a rectification of heave into an apparent horizontal velocity.’ Based on observations of ship motion, he estimated that a bias of about 0.01 m s\(^{-1}\) resulted from this rectification. Differences between buoy and ship responses to significant wind and wave conditions may magnify this value for buoy measurements.

The theoretical error in horizontal current measurement was estimated by assuming that the buoy behaves as a perfect wave rider of deep water waves. The 10-m discus is nearly a perfect wave rider for waves with a period greater than about 8 s, representing wavelengths that are ten times that of the diameter of the buoy hull. Based on the bottom depth, the assumption of deep water waves holds for waves of 15 s or less at the outer buoy and 22 s or less at the inner buoy. Neglecting velocities induced by buoy swing, the instantaneous difference between the horizontal buoy motion due to surface gravity wave orbital motion and the corresponding orbital motion at a depth \(z\), \(u_e\), can be described by
\[ u_c = a \sigma \left( \cos(-\sigma(t+\delta)) - \frac{\delta}{2} \left( \cos[k \tan \alpha - \sigma(t+\delta)] + \cos[-k \tan \alpha - \sigma(t+\delta)] \right) \right) \]

where \( a \) is the wave amplitude, \( t \) is time, \( d \) is the depth considered, \( \sigma \) is the wave frequency, \( k \) is the wave number, \( \alpha \) is the angle between the center of the acoustic beams and the vertical, and \( \delta \) is a phase. The maximum mean \( u_c \) over one sampling period of 255 s at a sampling rate of 1.5 s per ping was found in the range of phase shifts from -0.5 to 0.5 wave periods in increments of 0.1. The results of these calculations, shown in Fig. 8, reveal that the maximum theoretical error for horizontal current measurement at a depth of 104 m due to sampling only ranges from approximately \( \pm 0.006 \text{ m s}^{-1} \) per 2 m of significant wave height at a dominant wave period of 19 s to \( \pm 0.01 \text{ m s}^{-1} \) per 2 m of significant wave height at a dominant wave period of 6 s. From this it is shown that buoy motion may have induced some error into the horizontal current measurements, but that these errors are a small part of the total error.

Microbubbles (Thorpe 1986) invariably occur when white caps and breakers are present and are believed to affect the quality of measurements. Bubbles can degrade performance by reducing the efficiency of the transducer/water coupling, and by additional absorption and scattering. The acoustic scattering cross section \( \sigma \) of an air bubble in water is given by Medwin (1970) as

\[ \sigma(a, \omega) = \frac{4\pi a^2}{[1 - (\omega/\omega_0)^2]^{\frac{3}{2}} + \delta^2}, \]

where \( a \) is the bubble radius, \( \omega \) is the acoustic frequency, \( \omega_0 \) is the bubble's resonant frequency, and \( \delta \) is a damping coefficient. For the bubbles of interest, \( \delta \) ranges from 0.067 to 0.150 (Devin 1959). The resonant frequency \( \omega_0 \) is given by
where $\gamma'$ is the ratio of the specific heats $c_p/c_v$, $p$ is the hydrostatic pressure, and $\rho$ is the density of seawater. A plot of the variation of the scattering cross section of an air bubble at a depth of 1.3 m, for a sound source of 76 800 Hz, for a damping constant of 0.1, is shown in Fig. 9. The resonant radius (Thorpe 1982) as shown by the relative maximum of scattering cross section in Fig. 9, is 45 $\mu$m. Johnson and Cooke (1979) have reported that near this depth in coastal waters, when the wind speed is 11–13 m s$^{-1}$, there is a maximum number of bubbles in the size range from 42.5 to 59.5 $\mu$m. The fact that there is a maximum in 76 800-Hz acoustic energy scattering for the bubble size that is likely most abundant during periods of moderate to high wind and wave conditions suggests that a significant amount of the acoustic energy emitted from the transducer in high wind and wave conditions may be lost through scattering.

In the observation illustrated in Fig. 6, large negative vertical current measurements occur simultaneously with decreased echo levels and erratic horizontal currents between 1200 UTC 19 December 1991 (Julian day 353) and 1200 UTC 21 December 1991 (Julian day 355). Similar observations were reported from the six other useable bins at the outer buoy. Urick (1983) shows that the acoustic noise decreases with frequency in the band around 75 kHz, for sea state 3 and higher. If in high sea states, the ADCP detects random noise rather than properly correlated return signal, the red ambient noise spectrum could result in computation of negative along-beam velocities, and these in turn would result in biased estimates of vertical velocities. The effect on horizontal velocities is more difficult to determine.

In view of the errors in the data acquired during certain periods of high sea state, four quality control checks were applied at four depths at the inner buoy (56, 104, 152, and 200 m) and at two depths at the outer buoy (56 and 104 m). If any of the checks failed at any of the four depths at the inner buoy, or at either of the two depths at the outer buoy, then all the data at all depths for that particular buoy were deleted for that hour. Data acquired at the inner buoy from 0000 UTC 7 December 1991 to 1300 UTC 29 April 1992 and at the outer buoy from 0000 UTC 7
December 1991 to 1600 UTC 11 March 1992 were checked.

The first check deleted those horizontal current measurements that coincided with vertical velocity measurements greater than ±0.1 m s⁻¹. It is believed that extraordinary vertical velocities represent wave-induced buoy heaving, surging and swaying, or bubble-caused contamination. Depending on depth, from 4 to 6 h of vertical velocity measurements at the inner buoy, and 101 to 138 h at the outer buoy exceeded ±0.1 m s⁻¹. The more frequent occurrence of excessive vertical velocity measurements at the outer buoy can be attributed to the more severe wind and wave climate at its location.

The second horizontal current check deleted all measurements for which any of the hourly echo levels was less than 10 dB. Nine hours of data from the inner buoy and thirty-seven hours of data from the outer buoy were deleted because of this condition. Again, the higher number of hours of degraded data at the outer buoy reflects the more vigorous wave activity at the outer buoy.
A test for an hourly change in current exceeding three times the standard deviation of the hourly change in current, as determined from the entire record of measurements at the respective depth passing the first two checks, constituted the third check. Nineteen hours of data at the inner buoy and twenty hours of data at the outer buoy were deleted by this test and corresponded generally to periods of moderate to high sea state.

The fourth check deleted those observations taken during periods when the sea was vigorous enough to induce significant buoy motion and, therefore, bin mapping errors. If the ratio of significant wave height over dominant wave period was greater than 0.3 m s\(^{-1}\), and the significant wave height was simultaneously greater than 2 m, then all the horizontal current measurements for that hour were deleted. There were 73 h at the inner buoy and 177 h at the outer buoy that were deleted due to this condition.

Of the 3470 h of ADCP operation for which quality control checks were applied at the inner buoy, a total of 225 h of data were either missing due to communication failures, or were deleted using the aforementioned quality control checks, yielding an operational
Fig. 8. Potential magnitude of error in horizontal measurements at 104 m using an ADCP sampling at a rate of 1.5 seconds per ping over a 255-s period for 1-m-amplitude surface gravity waves.

system effectiveness of 93.5%. If the 60 hourly observations lost to communication failure are not counted, then 95.2% of the received data passed the quality control checks. Of the 2297 hours of operation for which quality control checks were applied at the outer buoy, a total of 391 hours of data were either missing or deleted, yielding 83.0% (85.7% ignoring communication losses) of the received data that passed the quality control checks.

The significant difference in operational system effectiveness at the two locations can be confidently attributed to the more severe wave climate at the outer buoy. The mean significant wave height over the time periods for which the checks were applied was 2.47 m at the outer buoy and 1.27 m at the inner buoy. The maximum significant wave height was 5.23 m at the outer buoy and 3.38 m at the inner buoy. The mean dominant wave period was 13.8 s at the outer buoy and 13.4 s at the inner buoy.

b. Means and fluctuations

In spite of periods where moderate to high wind and wave conditions caused degraded ADCP performance, the ADCP generally reproduced the current fluctuations observed by the VMCM, as illustrated in Fig. 4. The remainder of this section is devoted to quantifying the relative performance of the two systems after having eliminated periods when the ADCP was suspect, according to the checks enumerated above. On the in-shore mooring, VMCM and ADCP observations are available at five common depths: 24, 56, 104, 152, and 200 m. At the offshore site, the ADCP mooring was deployed in shallower water than the neighboring VMCM mooring. As a result, only three common depths were instrumented offshore: 24, 56, and 104 m.

The amplitude and direction of the mean current, along with the orientation of the major axis of the fluctuations, and the amplitude of the major and minor axes derived from the ADCP and VMCM measurements are listed in Table 2. In general, the agreement between the two sets of measurements is good. Amplitudes agree to within 0.01 m s⁻¹, which is equal to the short-term error, as defined by the manufacturer [Eq. (1)]. The direction of the mean current agrees to within a few degrees at all depths on the inshore mooring, and the same is true for the direction of the major axis. At the offshore site, larger discrepancies appear between the direction of the mean and major axis, as determined from the two sets of observations. This dif-
ference is attributed to the dissimilar depth in which the ADCP and VMCM moorings were deployed.

At each depth and for each mooring, time series of the difference between ADCP and VMCM velocity components were formed, and their statistics are also summarized in Table 2. In general, the mean speed difference corresponding to a bias error is of order 0.01 m s\(^{-1}\), while the combined variance of the two horizontal components of the difference time series is of order 0.0025 m\(^2\) s\(^{-2}\), based on hourly samples.

c. Regressions and correlations

To compare the performance of both instruments, regressions were performed between corresponding pairs of observations. The value of the north and east components of the horizontal current measured by the ADCP is plotted versus the same component measured by the VMCM for the 24-m depth at the inshore site in Fig. 10. If both instruments measured the same amplitude and direction of the current, all of the obser-

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**Table 2.** Basic statistics of the current observations when available at common depths. For the inshore (In) mooring, statistics cover the period 7 December 1991–24 April 1992. For the offshore (Off) mooring, statistics cover 7 December 1991–11 March 1992. Amplitudes are in meters per second, directions are in degree relative to true north. The last two columns describe the speed (m s\(^{-1}\)) of the time series of the difference between the ADCP and VMCM measurements, and the combined variance (m\(^2\) s\(^{-2}\)) for both components.

<table>
<thead>
<tr>
<th>Mooring depth</th>
<th>Amplitude of mean</th>
<th>Direction of mean</th>
<th>Major axis orientation</th>
<th>Major axis amplitude</th>
<th>Minor axis amplitude</th>
<th>Difference series</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ADCP</td>
<td>VMCM</td>
<td>ADCP</td>
<td>VMCM</td>
<td>ADCP</td>
<td>VMCM</td>
</tr>
<tr>
<td>In 24</td>
<td>0.05</td>
<td>0.05</td>
<td>40°</td>
<td>35°</td>
<td>-50°</td>
<td>-57°</td>
</tr>
<tr>
<td>In 56</td>
<td>0.06</td>
<td>0.07</td>
<td>6°</td>
<td>4°</td>
<td>-52°</td>
<td>-53°</td>
</tr>
<tr>
<td>In 104</td>
<td>0.06</td>
<td>0.05</td>
<td>7°</td>
<td>5°</td>
<td>-56°</td>
<td>-57°</td>
</tr>
<tr>
<td>In 156</td>
<td>0.06</td>
<td>0.05</td>
<td>2°</td>
<td>6°</td>
<td>-57°</td>
<td>-53°</td>
</tr>
<tr>
<td>In 200</td>
<td>0.05</td>
<td>0.05</td>
<td>6°</td>
<td>6°</td>
<td>-65°</td>
<td>-60°</td>
</tr>
<tr>
<td>Off 24</td>
<td>0.02</td>
<td>0.03</td>
<td>-19°</td>
<td>-50°</td>
<td>60°</td>
<td>73°</td>
</tr>
<tr>
<td>Off 56</td>
<td>0.04</td>
<td>0.03</td>
<td>5°</td>
<td>-4°</td>
<td>69°</td>
<td>72°</td>
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<tr>
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<td>4°</td>
<td>-8°</td>
<td>-76°</td>
<td>81°</td>
</tr>
</tbody>
</table>
Fig. 10. Scatter diagram of 1-h-average VMCM observations versus corresponding ADCP measurements. The instrument pair was 24 m beneath the surface on the inshore moorings. The crosses correspond to the north component of the current and the circles correspond to the east component.

The correlation coefficient is always significant and close to unity. There appears to be a trend of diminishing correlation coefficients with depth. The correlation coefficients obtained from the outer mooring, where the motion of the buoys was larger, are smaller than at the inshore mooring.

The phase of the complex regression slope is a measure of differences between the various compasses used on each instrument. The ADCP uses a single compass for all depth bins, while each VMCM has its own compass. On the inshore mooring, the phases computed at different depths change, with magnitudes of a few degrees, on the order of the errors expected from the compasses. On the outer mooring, the consistent -4.0° phase obtained for the three comparable depths suggests that the single compass mounted in the ADCP could have been biased relative to the VMCM compasses.

The slope of the regression line is a measure of the relative gain between the ADCP and VMCM observations. The lower amplitudes computed for the offshore mooring are probably due to the lower correlation between the measurements at that location.

d. Spectra and transfer function

Figure 4 illustrates a significant finding: there is more high-frequency energy in the ADCP records than in the VMCM records. Energy spectra can be used to estimate the transfer function between ADCP and VMCM observations as a function of frequency. Spectra of ADCP and VMCM observations from the inshore mooring are illustrated in Fig. 11. The method of rotary spectra (Gonella 1972) is used to compute the spectral estimates of the complex time series. Positive frequencies correspond to clockwise motions and negative frequencies correspond to counterclockwise motions.

The reliability of spectral estimates and estimates of transfer function characteristics depends on the number of degrees of freedom available for the estimation. Transfer functions computed from single pairs of observations were found to be noisy, due to the relatively short length of the records available. As the current velocities at various depths between 24 and 200 m are poorly correlated with each other, the average spectra and cospectra are determined for five depths where pairs of observations are available on the inshore mooring, thus effectively increasing the number of degrees of freedom by a factor of 5. As in deeper ocean records, the clockwise motions are seen to dominate the spectra. At frequencies greater than 0.1 cph, the ADCP spectrum is characterized by higher energy levels, and at frequencies greater than 0.2 cph, the ADCP spectrum flattens out, defining the noise level of that set of observations, while the VMCM spectral estimates continue to diminish. The flat portion of the ADCP spectrum is at a level of $2 \times 10^{-2}$ m$^2$ s$^{-3}$ (cph)$^{-1}$.

The transfer function between ADCP and VMCM observations, defined here as the ratio of the cospectrum to the spectrum of ADCP observations, is also illustrated in Fig. 11. At low frequencies, the transfer function of

| Table 3. Results of a complex regression analysis on corresponding pairs of instruments at different depths on either mooring. The correlation and regression slope are complex numbers. |
|-----------------|-----------------|-----------------|-----------------|
| **Mooring—depth** | **Correlation amplitude** | **Regression slope amplitude** | **Regression slope phase** |
| Inshore—24 m | 0.96 | 1.011 | 1° |
| Inshore—56 m | 0.96 | 0.934 | 2° |
| Inshore—104 m | 0.97 | 0.923 | 0° |
| Inshore—156 m | 0.96 | 0.915 | 5° |
| Inshore—200 m | 0.94 | 0.861 | 3° |
| Offshore—24 m | 0.92 | 0.934 | -4° |
| Offshore—56 m | 0.89 | 0.873 | -4° |
| Offshore—104 m | 0.86 | 0.963 | -4° |
function has an amplitude near unity. At higher frequencies, the transfer function amplitude decreases, as the ratio of the coherent energy between the two pairs of observations to the energy in the ADCP observations decreases.

e. Vertical structure

The topmost bin resolved by the ADCP is located 24 m beneath the surface, at a depth that could be beneath the mixed layer (ML) at times. To determine the ML depth, the temperature observations made with the VMCMs were analyzed according to the method proposed by Lentz (1992), and the mean depth of the layer was found to be 12 m, ranging between 6 and 60 m. Correlations between currents observed at 5, 10, and 24 m are greater than 0.9, and, thus, while the topmost ADCP bin is located beneath the mean position of the mixed layer, it is in the mixed layer during episodes of moderate to strong wind forcing. Even when located beneath the ML, the large correlations observed among the upper VMCMs suggest that 24-m observations are representative of the currents in the surface layers.

4. Vertical velocities

a. Mean vertical velocities

Vertical profiles of the mean error velocity, mean vertical velocity, and northward and eastward components of the current from the inner buoy are shown in Fig. 12. At the inner buoy the mean vertical velocity found from useable measurements acquired from 1 January to 30 April 1992 ranged around −0.01 m s⁻¹. Such persistently negative vertical velocities throughout the water column would represent a large downwelling current at these locations. Furthermore, it was found that there was a strongly persistent negative mean error velocity at both stations. The error velocity, as indicated earlier, is the difference between the two estimates of vertical velocity provided by the ADCP by virtue of its use of four acoustic beams. At the inner station mean values ranged from a −0.005 m s⁻¹ at 328-m depth to −0.4 m s⁻¹ at 24-m depth. The fact that the mean error velocities were approximately half of the mean vertical velocities suggests that there was an inherent bias in the RDI ADCP instruments mounted on both buoys.

One of the known sources of vertical velocities in the ocean is related to inhomogeneities in the atmospheric forcing over the ocean. Specifically, if the wind stress field has a nonzero curl, then vertical velocities are required by continuity to balance out the divergence in the Ekman transport in the mixed layer, induced by the variations in wind stress. Specifically, the vertical velocity \( w \) is related to the wind stress curl \( \nabla \times \tau \) by

\[
w = \frac{\nabla \times \tau}{\rho f},
\]

where \( \tau \) is the wind stress, \( \rho \) is the water density, and \( f \) is the Coriolis parameter. As the seasonally averaged winds are directed equatorward in the SCB, with increasing amplitudes offshore, the wind stress curl is generally positive, which would correspond to a positive vertical velocity, with maximum average velocities of order 0.001 m s⁻¹. This is in the opposite direction and
is much smaller in magnitude than the results illustrated in Fig. 12.

In the absence of a physically realizable mechanism responsible for the large mean vertical velocities reported by the ADCP, it may be recognized that geometrical errors in the construction of the instrument, and particularly in the alignment of the four acoustic beams, could result in some of the horizontal velocities being confused into the vertical velocity.

b. Diel migration of the scattering layer

The diel migration of scatterers has been shown to affect the vertical velocity measurements reported by ADCPs, as described by Plueddemann and Pinkel (1989), Smith et al. (1989), and Wilson and Firing (1992). The pattern of mean vertical velocity by depth and hour of the day, taken at the inner buoy from 1 January to 30 April 1992, was found to agree with the pattern found by Plueddemann and Pinkel (1989). There is strong downward motion at sunrise and a strong upward motion at sunset, as illustrated in Fig. 13. This persistent diurnal cycle of vertical velocity change coincides with a diurnal fluctuation in echo levels, and therefore coincides with the diel migration of sound scatterers (Fig. 14), presumably in response to changes in light level. These motions detected by the ADCP are thus motions of the scattering organisms, not the motions of the water.

c. Semidiurnal and internal wave periods

The VMCM arrays provide continuous records of temperature at the depths of the current meters. In the internal wave band of frequencies, between the inertial and buoyancy frequencies, it is expected that time changes in temperature at a given depth are mostly due to vertical advection. This is due to the relatively small effect of local heating, because the vertical gradient of temperature is generally much larger than the horizontal temperature gradients, and because vertical and horizontal velocities are of the same order. Under this assumption an estimate of the vertical velocity \( w' \) can be estimated from temperature observations as

\[
\frac{\partial T}{\partial t} = -\left( \frac{\partial T}{\partial z} \right)^{-1} \frac{\partial T}{\partial z}
\]

While the actual vertical velocity \( w \) may have a different amplitude, \( w \) and \( w' \) should at least be coherent in some part of the internal wave band.

Using the above assumption, the inshore mooring observations were used to estimate vertical velocity at 56 m beneath the surface. The time derivative of temperature was estimated by differencing the temperature observations at 56 m, while the vertical gradient of temperature was estimated by taking the difference between the temperature observations at 24 and 104 m. Time series of \( \Delta T/\Delta t \) and \( \Delta T/\Delta z \), and \( w' \) are illustrated in Fig. 15, along with observations of the vertical velocity \( w \) reported by the ADCP for the 56-m bin. The time

![Diagram](image.png)

**Fig. 13.** Mean vertical velocity at the inner buoy during the period 1 January–30 April 1992.
derivative of temperature exhibits fluctuations principally in the diurnal, semidiurnal, and higher frequencies. The vertical gradient in temperature shows some variability around a mean value 0.05°C m⁻¹. The large mean value of the temperature gradient, in comparison with fluctuations, suggests that it is reasonable to estimate the local gradient at 56 m using the difference between 24 and 104 m. Fluctuations in w' estimated from temperature gradients closely match fluctuations in the time derivative of temperature. Maximum amplitudes are of order 0.01 m s⁻¹, as expected in the thermocline. Vertical velocities reported by the ADCP show little correspondence with w'. The two variables are not significantly correlated. The ADCP velocities are an order of magnitude larger, and show a definite bias to negative values, corresponding to the mean downward velocities described earlier. Diurnal fluctuations in the ADCP velocities, corresponding to the diel migration of scattering particles are clearly evident between hours 200 and 300.

5. Summary

The study reported here confirms and extends results of previous comparison studies. It has been found that a 75-kHz ADCP mounted on a large surface buoy produces reliable estimates of the horizontal velocities, as long as the surface wind and wave field are not too large. Quantitative tests have been devised to determine when the buoy motion is likely to affect ADCP current measurement.

Time series of the difference between ADCP and VMCM horizontal velocities have an average of about 0.005 m s⁻¹, which is consistent with estimates of bias errors for the ADCP (RD Instruments 1989b; Chereskin and Harding 1993). The variance in the combined components of horizontal velocities is of order 0.0025 m² s⁻² for hourly sampled series. The spectrum of ADCP observations flattens out at a level of 2 × 10⁻³ m² s⁻² (cph)⁻¹ at frequencies above 0.2 cph. If the ADCP observations are low-pass filtered with a cutoff frequency of 0.1 cph (or approximately 0.5-day period), the resulting short-term error would be 0.01 m s⁻¹, equal to the short-term error expected from Eq. (1). The noise floor defined by the spectrum illustrated in Fig. 12 is dependent on the operating frequency of the ADCP system, sampling scheme, and other considerations. Deployments of higher operating frequency ADCPs or deployment on more stable platforms would be expected to result in lower noise levels.

In a configuration where the ADCP is mounted on a surface float, the topmost observation is located 24 m beneath the surface, for a 75-kHz unit. The results presented here suggest that in the SCB, even though the mixed layer did not always extend to that depth, the 24 m observations were representative of the currents observed at 5 and 10 m.

Although the mechanically sensing instruments used to compare with the ADCPs did not observe vertical velocities, the values of this parameter reported by the ADCP are deemed unreliable for three reasons. First,
the time average, or bias, of the vertical velocities over nearly four months is of order 0.01 m s$^{-1}$ and directed downward, a value that exceeds by one or two orders of magnitude values expected to be found in the area where the comparison took place. Second, the diel migration of the scattering layer produces a signal that the ADCP is unable to distinguish from water motion, as reported by previous authors. Finally, vertical velocities reported by the ADCP are uncorrelated in the internal wave band to vertical velocities inferred from temperature measurements. Also, the existence of bubbles has been identified as a possibly deleterious effect on vertical ADCP velocities.

This comparison suggests that the ADCP produces accurate horizontal current profiles, particularly if the observations are averaged over time periods of 0.5 days or longer. The real-time monitoring of ocean circulation in areas of active offshore oil and gas development is seen as a major potential use of the ADCP–NDBC buoy system. Analysis of multiyear records of coastal ocean currents derived from this system may provide new insights into climatic processes taking place in the ocean. The relative ease of deploying and maintaining such systems over long time periods offers the potential of obtaining long time series of currents in the coastal ocean, similar to the time series of atmospheric forcing that have been available to the meteorological community for nearly a century.

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