Comparison of Acoustic Doppler Current Profiler and Vector Averaging Current Meter Measurements in a Stratified, Freshwater Bay

PAPER

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ABSTRACT

The performance of a moored, upward-looking acoustic Doppler current profiler was compared with vector averaging current meters at three depths in a shallow, stratified bay during a 142-day period. Mean current speeds during the period agreed to better than 0.2 cms^{-1} and 5 degrees in direction. Scatter plots showed instantaneous differences of up to 10 cms^{-1} which were related to the active internal oscillations and episodes of large wind-induced temperature changes together with the 0.5 km separation of the two moorings.

INTRODUCTION

The acoustic Doppler current profiler (ADCP) is one of the newer technological developments in current velocity measurement instrumentation. Current velocities are determined by measuring the Doppler frequency shift between the transmitted and the backscattered signals. Offering numerous advantages, such as the measurement of the current profile over several hundred meters depth, durability with no mechanical parts, and the availability of vessel mounted or self-contained models, ADCPs have become the instrument of choice for the measurement of currents. In situ comparisons of ADCP data with data from other types of current measuring instruments, which have known response characteristics, made under a wide range of dynamic conditions are important in assessing the validity of the data. These types of comparisons have been reported (e.g., Magnell and Signorini, 1986; Pettigrew et al., 1986; Schott and Johns, 1987; and Johns, 1988); however, they were done with a variety of ADCP models or prototypes and were generally for short durations (<1 month) in high energy (>50 cms^{-1}) environments.

In this paper we compare current data measured by a moored, upward-looking, 600 kHz RD Instruments ADCP with data from three EG&G vector averaging current meters (VACM) moored nearby in a low energy (mean speed <10 cms^{-1}), shallow, thermally stratified, freshwater bay during a 142-day period. The response characteristics of VACMs are well known (e.g., Karweit, 1974; McCullough, 1975; Saunders, 1980; Beardsley, 1987), and these meters have been historically considered one of the standards by which to judge the performance of other subsurface current measuring instruments (Terry, 1986). Newer vector measuring current meters (VMCMs) were not available to us for comparison.

MEASUREMENT ENVIRONMENT

Green Bay is an elongated, 200 km-long bay connected to Lake Michigan by four passages at its northern end (Figure 1). The mean depth of the bay is about 15 m with the deepest region in the northern half. The bay has a mean width of 22 km. Thermal (density) stratification commences in late May, reaches maximum strength (~1°C m^{-1}) during mid-July through August at a depth between 10 and 18 m (average depth 14 m), then deepens and decays by early October (Gottlieb et al., 1990). The thermocline region is highly active with 6 m vertical displacements common in response to wind stress episodes and the resulting forced and free internal oscillations. Periods of these oscillations range from eight days through near-inertial and lunar tidal (17 to 12.4 hrs) to various free surface seiche modes (10 to 4 hrs). Currents flowing through the 10 km-wide constricted midsection of the bay are bidirectional and often in opposite directions above and below the thermocline during stratification (Miller and Saylor, 1985, 1993; Gottlieb et al., 1990). Since the bay is narrow, winds are fetch limited except along the major axis of the bay and wave heights seldom exceed 1 m.

During an Environmental Protection Agency sponsored Green Bay Mass Balance Study in the summer of 1989, an ADCP was moored near the midsection of Green Bay in 34 m of water within 500 m of a mooring supporting three VACMs and 240 m from a thermistor chain. A schematic of the moorings is shown in Figure 2.

CURRENT METER SETUP

The ADCP determines current velocity by measuring the Doppler shift in frequency between the transmitted signal and the echo signal reflected from scatterers in the water. Doppler-shifted frequency is linearly proportional to the relative velocity between the scatterers and the instrument. Range-gating the echo signal segments the acoustic path into depth cells or bins, and a velocity is computed for each bin.

FIGURE 1. Bathymetry of Green Bay and location of the mooring site.

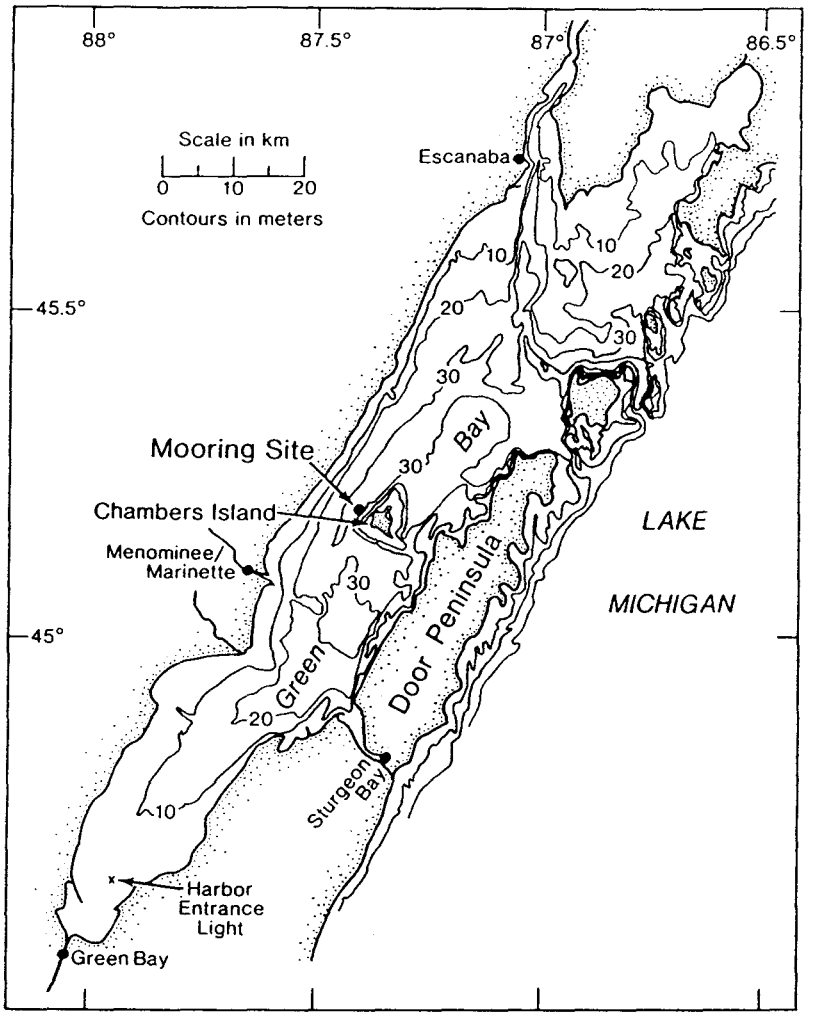
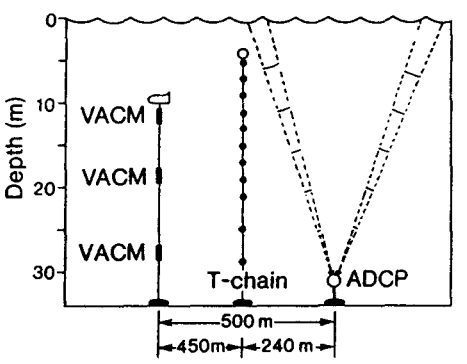


FIGURE 2. Schematic diagram of the VACM, ADCP, and thermistor moorings and their respective separation distances.



The 614.4 kHz ADCP has four acoustic transducer heads equally spaced in the azimuth (JANUS configuration) with a 30 degree beam angle relative to the vertical. The upward-looking ADCP was programmed for 30 1-m depth bins, a 2-m pulse length, and a 1-m blanking interval (a short time interval to allow the transducer ringing to diminish). The 2-m pulse length reduces the tracking lowpass filter skew and the velocity standard deviation. Ensemble averages were computed in earth coordinates using 400 pings over 15-min intervals. Only those pings that met the "goodness" test (25% of the pings exceed the signal-to-noise threshold of 6dB) were accepted, and the velocity data were corrected for speed of sound at the transducer head. Random errors in ensemble averages are less than 1.3 cms^{-1} for the setup parameters given above based on the manufacturer's criteria. Firmware version 16.27, which minimizes lowpass-filter skew errors and noise bias errors (Chereskin et al., 1989), was used to program the ADCP. The profile extended over 30 bins with the top bin centered +0.5 m above the water surface to the deepest bin centered at the 28.5 m depth. Near-surface contamination, caused when side-lobe returns from the water surface overpower the side-lobe suppression of the transducers, seriously degrades the data quality in the upper 15% of the acoustic range. The range of acceptable data, R_{MAX}, is approximated by

$$R_{MAX} = D \cos \Theta$$

where D is the distance from the ADCP to the surface and Θ is the angle of the beam relative to vertical (RD Instruments, 1989a; Appell et al., 1991). The contaminated region is in the upper 4.5 m for this mooring. Data were averaged to hourly values. More in-depth details of ADCP theory, operation, setup, and data processing have been well described in other publications (e.g., RD Instruments, 1989a; Johns, 1988; Schott and Johns, 1987) and will not be repeated here. The ADCP, mounted in an 81 cm syntactic foam sphere and mooring frame, was deployed in 34 m water with the transducers 4 m above bottom.

The VACM utilizes a Savonius rotor, a mechanical vane follower, and a magnetic compass to time-average east and north displacements and velocity. The manufacturer's specified accuracy is 5 degrees in direction with a 2.5 cms^{-1} threshold speed. VACMs were positioned under an aluminum torpedo-shaped subsurface float (230 kg buoyancy) at 12 m, 19 m, and 28 m depths and sampled at 15-min intervals then averaged to hourly values.

RESULTS

ADCP Profiles

Two acoustic beams are necessary to compute one horizontal current component and

a vertical velocity; the other beam pair computes the other horizontal component and a second vertical velocity. The difference between the two independent estimates of vertical velocity is termed the error velocity (RD Instruments, 1989a) and is useful for evaluating data quality. Nonzero error velocity values indicate either that the equipment is malfunctioning or that horizontal inhomogeneities in the water are present.

Means and standard deviations of the horizontal and vertical current components, error velocity, and scalar speed for each of the 30 bins over the 142-day interval provide an indication of data consistency. In bins 2 (–27.5 m depth) through 24 (–5.5 m) (the bins within the 85% profile range not contaminated by side-lobe energy), the mean magnitudes of the long-period-averaged horizontal current components are very small (<1 cms^{-1}), which is to be expected in polarized flow, but do show the dominant two-layer flow regime during the thermally stratified season. Scalar speeds average 6.7 cms^{-1} with a range of <1 cms^{-1} over the 23 bins. The error velocity has a consistent small negative bias (–0.09) and standard deviation of ±0.28 cms^{-1}. The vertical velocities also show a negative bias but, in general, are near zero.

Side-lobe contamination results in increasingly large positive values of echo intensity and current parameters and their standard deviations in bins 25 (–4.5 m) to 30 (+0.5 m). The 142-day mean speed at –1.5 m, for example, was 34(±15) cms^{-1}, which is nearly 4.5 times the mean speed, 7.6(±5.0) cms^{-1}, at –5.5 m. This is in contrast to data presented by Schott (1986), Schott and Johns (1987), and Appell et al. (1991), who showed that side-lobe contamination biases the velocity values towards zero as the water surface is approached and intersected. Their explanation was that the additional energy from the vertically traveling side-lobe signal, which has essentially no Doppler frequency shift, causes the bias toward lower Doppler frequencies (velocities). As in the above referenced studies, echo intensity reached a maximum (~80 dB) at bin 28 (–1.5 m), which corresponds to the return of the main and side-lobe beam echoes from the surface. Subsequent ADCP deployments in different lake and channel environments have shown similarly large positive values as the water surface is approached. Causes for these increases may lie in the fact that smaller waves appear to have a greater biasing effect than larger waves (Appell et al., 1991) and that the pulse length was set to twice the bin length, which reduces the spatial resolution. Also, wind-driven currents are largest at the surface; some small part of the speed increase could be real.

Bin 1, centered at the 28.5 m depth, is at the level nearest the depth of the lower VACM (–28.2 m). However, the manufacturer recommends that data from bin 1 not be used because low initial backscatter relative to transducer ringing will adversely affect this bin (RD Instruments, 1989b). This effect was demonstrated in our data by inconsistencies which appeared as a –1.2 cms^{-1} mean bias in the U-component and –2.2 cms^{-1} mean bias in vertical velocity when compared to bin 2, a factor of 5 change. The standard deviations are nearly equal for all bins, including bin 1, in the 85% range, which precludes using this statistic for determining data quality. The velocity error value is very near zero (–0.03) implying horizontal homogeneity in the water. Low-pass filter skew errors described and numerically estimated by Chereskin et al. (1989) are not significant since the current shear in the lower 30% of the profile is generally not large. Because of biases in bin 1, data from the 27.5 m depth (bin 2) will be used for the comparison with VACM data from –28 m.

ADCP - VACM Comparisons

Table 1 presents the means and standard deviations of the east (U) and north (V) components and scalar speed (S) for the VACM and ADCP pairs at the three depths for the 142-day measurement period. Because of the absence of significant steady currents in Green Bay, near-zero vector mean speeds cause resultant velocities to be uninformative. Standard deviations of both current components and the scalar speed for the two meter types and for the three depths are nearly equal. The last column in Table 1 gives the arithmetic average of the hourly current directions. Recognizing that there are inherent problems in scalar-averaging azimuths, the near-equal mean values suggest that both types of meters were measuring similar directions.

Table 2 presents the difference (ADCP minus VACM) statistics from hourly current components, speed, and direction data. Current component differences are less than 0.4 cms^{-1} and standard deviations less than 3 cms^{-1}. The small negative biases in the U-component and

TABLE 1. ADCP and VACM current meter statistics May 23-October 11, 1989.

Meter Depth (m)	Meter	U (U_{sd}) (cm/s)	V (V_{sd}) (cm/s)	Scalar SPD (S_{sd}) (cm/s)	DIR (deg)
–12.5	ADCP	–0.1(±5.8)	–0.1(±5.2)	6.7(±3.9)	171
–12.0	VACM	+0.2(±5.4)	–0.2(±5.5)	6.7(±4.0)	169
–19.5	ADCP	–0.4(±6.2)	–0.4(±5.2)	6.9(±4.4)	168
–19.0	VACM	–0.2(±5.7)	–0.5(±5.5)	6.8(±4.2)	166
–27.5	ADCP	–0.2(±6.5)	–0.5(±5.7)	7.2(±4.8)	165
–28.2	VACM	–0.1(±6.0)	–0.6(±6.2)	7.3(±4.7)	161

TABLE 2. ADCP minus VACM difference statistics (cms^{-1}) May 23-October 11, 1989.

Depth (m)	Del U Mean (sd)	Del V Mean (sd)	Del Spd Mean (sd)	Del Dir Mean (sd)
−12	−0.3(±2.7)	0.2(±2.4)	0.0(±2.4)	7(±37)
−19	−0.2(±2.3)	0.1(±1.9)	0.1(±2.1)	5(±35)
−28	−0.2(±2.2)	0.1(±2.0)	−0.1(±2.1)	2(±35)

the positive biases in the V-component may indicate slight compass differences. Speed differences, which are free of compass biases, are very near zero with standard deviations less than 2.5 cms^{-1}.

While the above mean and difference statistics illustrate excellent correlation between the two current meter types at the three depths when averaged over the 142-day measurement period, substantial instantaneous velocity differences are present. Scatter plots of the four parameters for each depth for the 142-day period and the unweighted linear regression statistics are presented in Figures 3, 4, and 5. These plots show that speeds are generally less than 20 cms^{-1} while 87%, 92%, and 93% of the scatter was less than ±4 cms^{-1} from unity for the 12, 19, and 28 m depths, respectively. A sample time series of current speeds measured by the ADCP and VACMs at the three depths and of contoured temperature data for a 20-day period in July 1989 is shown in Figure 6. The larger differences at the 12 and 19 m depths are correlated with episodes of either low current speeds and changing directions at one of the meter locations or intense, oppositely directed two-layer flow associated with large vertical thermal and current gradients at the comparison depth. For example, on July 14, temperature gradients of 4°C and current shear as high as 11 cms^{-1} between the 11 and 13 m depth resulted in greater than 8 cms^{-1} speed differences and >90 degree direction variations between meters at the 12 m depth. The large discrepancies in direction indicate that the two meters were not measuring in the same water mass because of the 0.5 km mooring separation. The largest differences at the 28 m depth are linked to episodes during which significant temperature changes penetrated to this depth, thereby disrupting stratification. These events occurred when wind episodes of sufficient strength and duration displaced the normally cool bottom-layer water with warmer water from southern Green Bay. This occurred most often in spring prior to the establishment of more stable summer conditions. During the fall cooling phase, variability near the bottom again increased as the upper levels cooled and the water mass approached near isothermal conditions. For this reason, the ADCP-VACM differences between depths for the 142 days were comparable in magnitude but not highly correlated (R<0.25). Spectral analysis of the component differences showed significant energy at the inertial frequency (1.4 cpd) at the 12 m depth, while the spectra at the other two depths was red, with no discrete frequencies showing significant energy. This is consistent with the forcing described above. Also, the regression coefficients and correlation during the 30 days with strongest stratification were nearly equal to those for the 142-day period.

In summary, the comparison of currents measured by an upward-looking ADCP with VACMs at three depths show very good correlation and are well within the accuracy of the instruments during a 142-day deployment. In the low current velocity environment of Green Bay, mean current speed differences agreed to better than 0.2 cms^{-1} and standard deviations were less than 2.5 cms^{-1}. This compares with standard deviations ranging from 3-to-6 cms^{-1} reported by Magnell and Signorini (1986) and Bos (1991) in other comparison studies. Thermal (density) stratification with large internal oscillations coupled with the 0.5 km spatial separation of the two moorings were the primary cause of instantaneous current differences.

FIGURE 3. Scatter diagram of ADCP versus VACM zonal (U), meridional (V), speed (S), and direction data observed from May 23 through October 11, 1989. Dashed line is the least-squares fit (Y = a + bX) and R is the correlation coefficient. Depth of the data comparison 12 m.

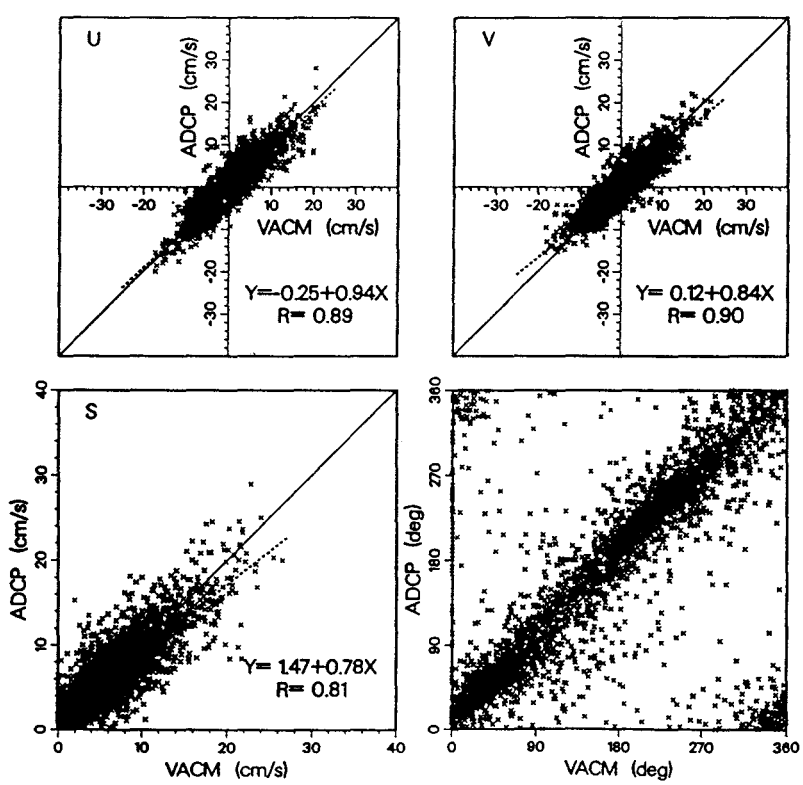


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FIGURE 4. Scatter diagram of ADCP versus VACM zonal (U), meridional (V), speed (S), and direction data observed from May 23 through October 11, 1989. Dashed line is the least-squares fit (Y = a + bX) and R is the correlation coefficient. Depth of the data comparison 19 m.

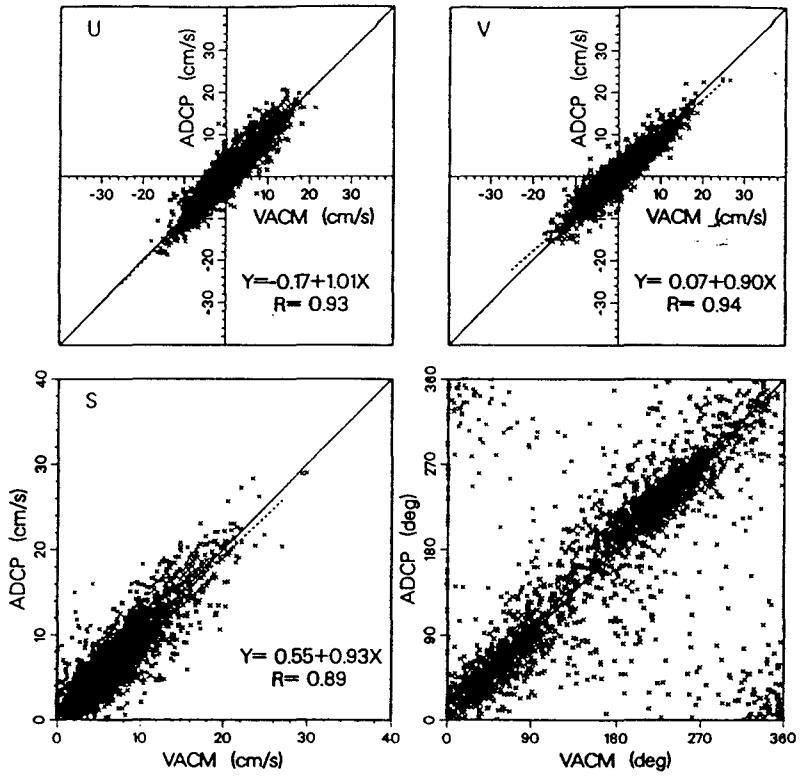
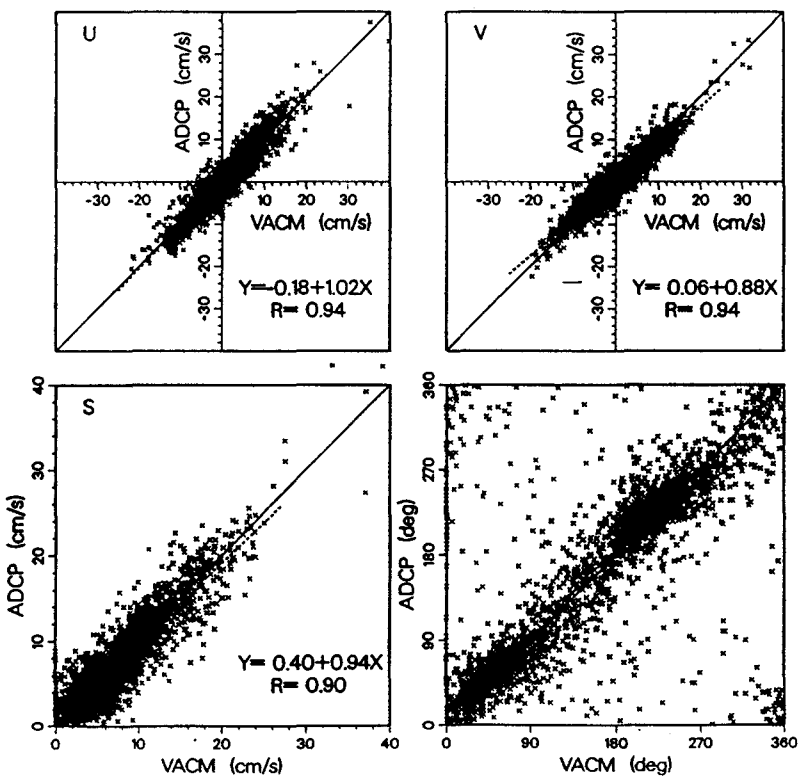


FIGURE 5. Scatter diagram of ADCP versus VACM zonal (U), meridional (V), speed (S), and direction data observed from May 23 through October 11, 1989. Dashed line is the least-squares fit (Y = a + bX) and R is the correlation coefficient. Depth of data comparison 27.5 m (ADCP mid-bin depth) and 28.2 m (VACM depth).



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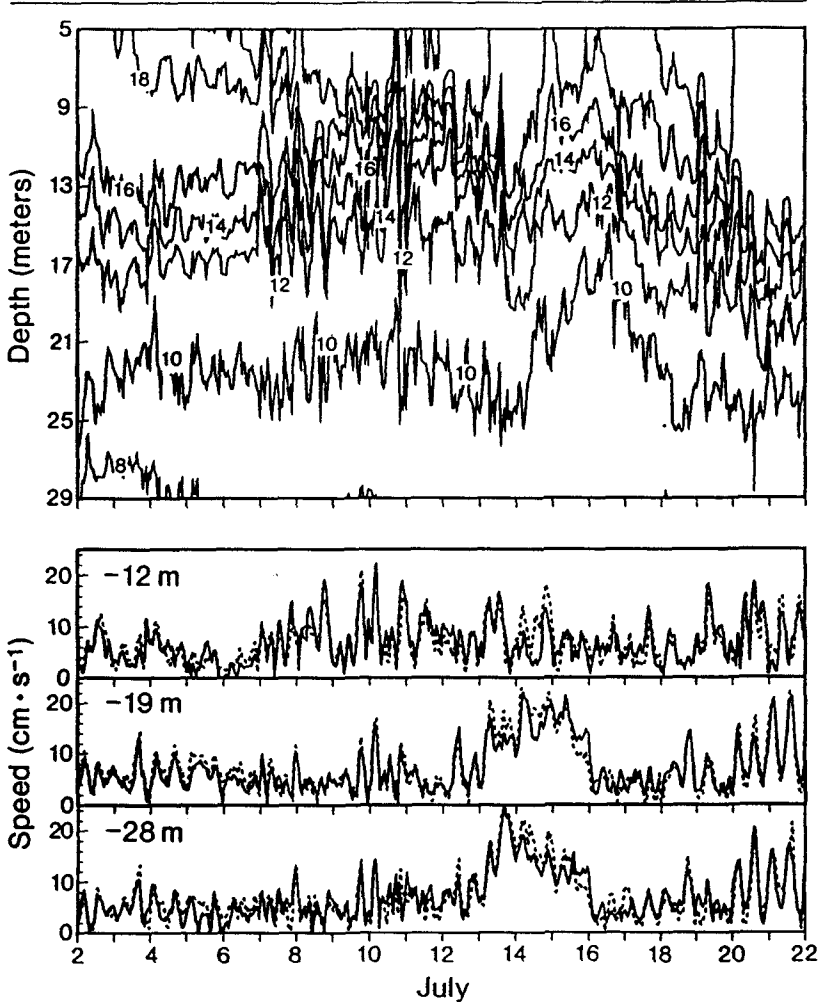
FIGURE 6. Contoured temperature data (2°C intervals) are shown in the upper panel and the lower panel shows ADCP (dash) and VACM (solid) current speeds for July 2–21, 1989, at the indicated depths.