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Mysis Vertical Migration in Grand Traverse Bay, Lake Michigan, Observed by an Acoustic Doppler Current Profiler

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ABSTRACT. *The acoustic return signal from Acoustic Doppler Current Profilers (ADCP) moored in Traverse Bay during a 90-day summer period showed a rapid 5-10 dB increase about 1/2 hour after sunset and a similar decrease 1/2 hour before sunrise. The pattern is characteristic of zooplankton diel vertical migration, most likely* Mysis relicta. *These are the first reported observations of freshwater invertibrate migrations using ADCP backscatter. A 15–20 m thick sound scattering layer also persisted throughout the summer. This layer, constrained between the 6°C and 10°C isotherms, generally followed the internal thermocline fluctuations. These backscatter data demonstrate that determining characteristics of diel migration, and monitoring zooplankton temporal and spatial variability are possible using ADCPs.*

INDEX WORDS: *ADCP, backscatter, zooplankton, DVM, Traverse Bay, Lake Michigan.*

INTRODUCTION

Physical measurements and extensive atmospheric and bio-geochemical sampling were conducted in the west arm of Grand Traverse Bay, Lake Michigan, in an effort to better understand the persistent transfer of atmospheric and sedimentary contaminants into the Great Lakes fish in spite of large reductions or elimination of inputs (Eadie *et al*. 2000, Masterson 2001). Acoustic Doppler Current Profilers (ADCP) and thermistor chains measured current velocity and water temperature profiles from mid-June through mid-September 1997. Though the original purpose of the ADCP deployments was to measure current velocity profiles in Grand Traverse Bay, visual inspection of the echo return, or backscatter, profiles revealed large amplitude diurnal box-type-wave oscillations. The distinguishing features of the observed pattern are its temporal and spatial persistence throughout the 90-day observation period and in-phase relation with solar time. The hypothesis is that these large, persistent backscatter oscillations are a signature of the diel vertical migration (DVM) of zooplankton, and more specifically, *Mysis relicta*. In the marine environment, Schott and Johns (1987) were the first to report a diurnal pattern in the backscattered signals and vertical velocities measured by an upward-looking 150 kHz ADCP in the high-speed Somali Current during a 7-month deployment. They attributed this diurnal pattern to the DVM of biological scatterers. Flagg and Smith (1989) modified a 300 kHz ADCP to measure zooplankton abundance by correlating the backscattered acoustic signals with zooplankton samples collected with a net and concluded that it is possible to predict zooplankton biomass to ±15 mg m^{-3}, but only after careful calibration of the transducers and electronics. The number of marine deployments of ADCPs continues to increase our knowledge of the vertical migration behavior of zooplankton (e.g., Schott *et al*. 1993, Wilson and Firing 1992, Fischer and Visbeck 1993, Rippeth and Simpson 1998). Using ADCP backscatter to study vertical migration in freshwater, however, has not been reported.

In the Great Lakes, opossum shrimp *Mysis relicta* are an important component in the food chain and are one of the planktonic organisms that exhibit DVM behavior. Pioneering studies on the vertical migration of *Mysis relicta* in Lake Michigan by Beeton (1960) confirmed that the migration patterns

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seen in marine environments also occur in fresh water (see Beeton and Bowers 1982, for a review). Sampling the upper 40 m at a 74-m-depth station in Lake Michigan, Beeton (1960) observed that the initial upward migration extended to about the 10 m depth at dark, with the peak abundance (~17 m^{-3}) occurring at the 20 m depth before midnight. As dawn approached, the *Mysis* descended below the sampling depth. The water temperature at 10 m was 15°C, which may have been the reason for their descent to the 20 m depth, where the temperature was a more favorable 9°C. Smith (1970) reported that mysids do not tolerate temperatures > 10°C in the hypolimnion and > 14°C in the epilmnion for extended periods. Robertson *et al.* (1968) observed that mysid abundance increased with depth at six Lake Michigan stations ranging in depth from 17 to 262 m. Similarly, Carpenter *et al.* (1974) reported that mysid densities increased with depth down to 200 m in Lakes Huron, Ontario, and Superior. Later Great Lakes studies showed similar behavioral patterns; however, significant differences in population estimates were attributed to sampling depth differences and variations in the types of sampling gear (Sell 1982). Pothoven *et al.* (2000) compared the 1990s mysid population estimates in Lake Michigan relative to the ongoing ecological changes and concluded that abundances appear stable compared to 1950s and 1980s population estimates. Results from oblique net tows, benthic sled tows, and fish stomach contents verified that mysids are an important component of the food web in Grand Traverse Bay (Masterson 2001).

This paper presents backscatter data measured from a moored ADCP in a freshwater environment. This type of measurement can be an important tool for characterizing diel vertical migration and provide insight into the temporal and spatial variability of biological scatterers.

METHODS

Two current meter/water temperature moorings were deployed 18 June 1997 (Fig. 1) in the western arm of Grand Traverse Bay in northeastern Lake Michigan. A 300 kHz RDI Workhorse Acoustic Doppler Current Profiler (WH-ADCP) was moored 9 m below the surface in a downward-looking mode at each site. An 810 mm syntactic foam subsurface buoy, designed for the WH-ADCP, provided about 100 kg reserve buoyancy. Mooring information and ADCP setup parameters are given in Table 1. On the southern mooring, 5, an Aanderaa 40-m thermistor chain measured hourly water temperatures at 4-m intervals from depths of –13 m to –53 m. ADCPs also measured water temperature at the transducer head. Five Brancker T-1000 temperature loggers were attached to the mooring line at mooring 7 with a 4-m spacing beginning at –13 m and sampled at 15-minute intervals. A hardware-limiting problem in both WH-ADCPs resulted in low echo intensities in bin #1 which caused the internal data quality checking routine to reject the data from that bin. The ADCP at mooring 7 failed after 6 days.

Four transducers in the ADCP head, with 90° azimuthal spacing inclined 20° from the vertical, transmit an acoustic pulse and receive the echo return signal reflected from scatterers in the water. These scatterers are small particles in the water, such as plankton, sediment, or bubbles. The return

TABLE 1. Mooring locations and instrument setups.

Moorings	**5**	**7**
Location	44°49.39′ 85°37.41′	45°01.68′ 85°33.05′
Water Depth	94.5 m	118.0 m
Deployed	18/06/97 1030 EST	18/06/97 1300 EST
Retrieved	16/09/97 1700 EST	17/09/97 1100 EST
Profilers:		
ADCP	300 kHz	300 kHz
No. cells	45	55
Cell size	2 m	2 m
# pings	400	400
Sampling interval	30 min	30 min
ADCP Depth	8.8 m	8.8 m
Depth first good cell	15 m	15 m
Temperature:		
Instrument	Thermistor chain	Temperature loggers
Sampling interval	1 hour	15 min
Depths	13–53 m, 4-m intervals	13–29 m, 4-m intervals
Available Data		
Currents/ Backscatter	18/06/97–16/09/97	18/06/97–24/06/97
Temperature	18/06/97–16/09/97	18/06/97–16/09/97

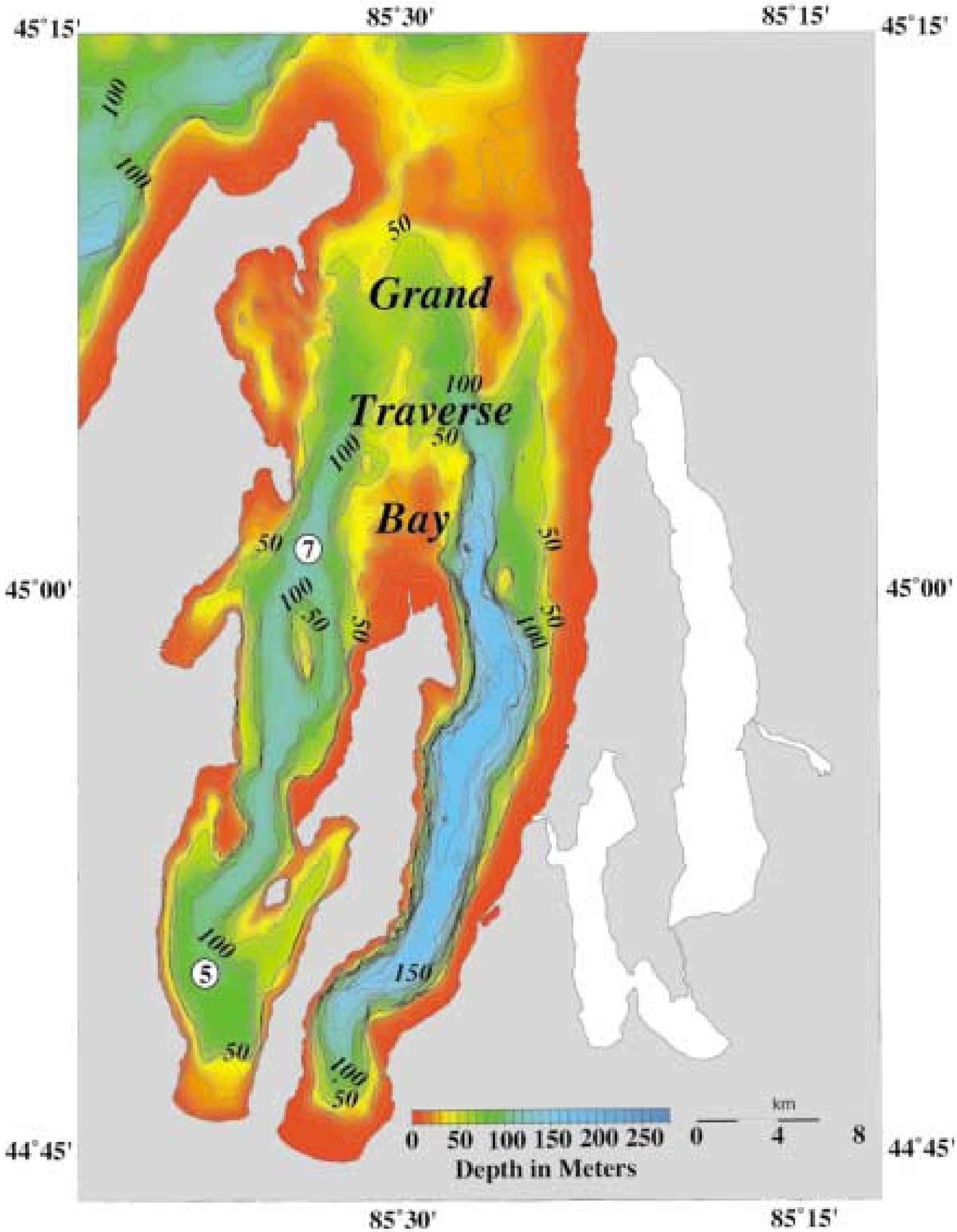

FIG. 1. Grand Traverse Bay bathymetry and location of moorings 5 and 7.

echo intensity is range-gated, which breaks the return signal into successive depth cells, or bins. Two horizontal current components and a vertical current component are computed at each depth cell using the Doppler principle. Each depth cell is processed independently, thereby producing vertical profiles of the horizontal current components, vertical velocity, and echo intensity. Comparisons of ADCPs and conventional Savonius rotor current meters show excellent correlation for horizontal velocities (Miller and Saylor 1993, Appell *et al.* 1991, Pettigrew *et al.* 1986). Vertical velocity accuracy, however, is not as readily verifiable because of the small magnitudes and the difficulty in making validating measurements.

Echo intensity is generally reported in terms of the volume scattering strength (Medwin and Clay 1998)

$$S_v = 10\log_{10}(I_R / I_I) \tag{1}$$

where S_v is the volume backscattering strength in dB, I_R is the returned intensity, and I_I the incident or transmitted energy. Received backscatter power is a nonlinear function of (1) the strength of the transmitted power, (2) properties of the receivers, (3) the loss of energy through sound absorption and beam spreading, and (4) the effective cross section area and characteristics of the reflecting particles. At a specific range, or distance from the instrument, the temporal variations in backscatter signal intensity at that range are dependent only on the concentration and reflectivity of the scatterers. To compare return echo intensities between ranges, for example vertically through the water column, requires that the ADCP echo intensity profile be corrected for range-dependent effects, namely beam spreading and signal absorption. Absolute backscatter values, that is, values that are instrument independent, require that parameters (1) and (2) above are known. However, this requires that each unit go through extensive calibration procedures that are not routinely available and have not been done for these instruments.

To compensate for the range dependent losses due to beam spreading and water absorption, Deines (1999) developed a working version of the sonar equation:

$$S_v = C + 10\log_{10}((T_x+273.16)R^2) - L_{DBM} - P_{DBM} + 2\alpha R + K_c(E - E_r) \tag{2}$$

where S_v is the backscattering strength in dB, C is a variable containing parameters that are measured and inferred (e.g., transducer efficiency and diameter, beam angle, and noise bandwith), T_x is temperature of the transducer (°C), R is the slant range to the depth cell (m) which accounts for the beam angle (θ) and variations in the speed of sound due to water temperature variations, L_{DBM} is $10\log_{10}$(transmit pulse length (m)), P_{DBM} is $10\log_{10}$(transmit power (Watts)), and α is the absorption coefficient for fresh water (dB/m). E is the data output (in counts) derived from the Received Signal Strength Indicator (RSSI) of the receiver for each beam that is proportional to the logarithm of power and converted to dB units by the factor K_c. E_r is the real-time RSSI value with no return signal. Slant range R is

$$R = \{[B+(L+D)/2 + ((N-1)*D)+ (D/4)]/\cos\theta\} * (c'/c_1) \tag{3}$$

where B is the blanking length (m), L the pulse length (m), N the cell number, D the cell length (m), c' is the average sound speed from the transducer to the range cell, and c_1 is the speed of sound at the instrument. The D/4 term accounts for the fact that the BroadBand ADCP samples the echo intensity in the last quarter of each depth cell, not the center. The above terms are selected during instrument setup, and the average sound speed from the instrument to the individual cell requires water temperature profile data. "Typical" values are assigned to instrument dependent parameters that are not available for the individual instruments. After applying the range effect corrections, vertical backscatter variability is, then, only a function of the density and properties of the scatterers.

RESULTS AND DISCUSSION

Echo return data from the four beams were averaged for each cell and, with the temperature profile data, backscatter intensity profiles were calculated by applying the modified sonar equation described above. The backscatter intensities measured in Grand Traverse Bay show a dramatic diurnal variability. An examination of the first 14 days of data from mooring 5 show sharp increases (5–10 dB) in backscatter in water depths greater than 35 m (Fig. 2, top panel). A difference of 10 dB represents an order of magnitude change in acoustic reflectivity or, equivalently, the number and/or effective cross section of scatterers. The sharp increases occurred at about 2100 EST with equivalent decreases at 0430 EST (Fig. 2). These times are about 1/2 hour after local sunset (2031 EST) and 1/2 hour before sunrise (0456 EST), which is very near Civil Twilight (2109/0419 EST for 20 June 1997) for the Grand Traverse Bay area. The 6 days of available backscatter data from mooring 7 (not shown), 10 km north near mid-bay, exhibited a nearly identical pattern, indicating the phenomenon is bay-wide. The nocturnal backscatter pattern and the temporal spreading of this band with the lengthening of time between sunset and sunrise strongly suggests that the scatterers are a zooplankton species that exhibits DVM behavior. The dominant zooplankton in Grand Traverse Bay that exhibit DVM is *Mysis relicta*. Mysids are of sufficient size, up to 20 mm, to be easily detected by a 300 kHz ADCP. Other freshwater zooplankton, *Limnocalanus* copepods (1.3–2.9 mm), *Diaptomus* adults (1–1.5 mm in length), and possibly even *Nauplii* (0.1–0.4 mm), may contribute to the observed vertical migration. The animals did not rise above the 30-m depth during the first week even though the water temperature at that depth was < 5°C (Fig. 2). However, the moon was full, skies were mostly clear, and transmittance exceeded 83% throughout the water column during mid-June. Beeton (1960) reported that mysids respond to light levels to 10^{-4} lx and observed less vertical movement on moonlit nights during his Lake Michigan study. Water temperature contours (Fig. 2, lower panel) show a sharp thermocline, ~1°C m^{-1}, above the 20-m depth at the beginning of the period, upwelling 25–28 June, followed by some oscillations and deepening of the thermocline. Based on Beeton's (1960) observations, mysids initially migrate through the thermocline, but later in the evening aggregated in or below this layer. Even though mysids are content in temperatures to 10°C (Smith 1970), and in-lab maximum feeding rates were observed at 12–14°C (Rudstam *et al*. 1999), the extent of the vertical excursions during spring and early summer in Grand Traverse Bay is limited by light, not water temperature.

Assuming that the zooplankton are migrating upward to feed, the signature of the migration should be observed in the vertical velocities measured by the ADCP. The rapid increase/decrease in observed backscatter over 1 hour or less translates into a vertical speed of about 1–2 cms^{-1}, assuming these animals migrate on the order of 80 m. Beeton (1960) reported *Mysis relicta* ascending and descending at speeds of 0.8–1.3 cms^{-1} with a maximum amplitude of 76 m; McNaught and Hasler (1964) estimated a speed of 0.5 cms^{-1} with a vertical amplitude of 40 m. *In situ* observations from a submersible measured upward swimming speeds of 2–5 cms^{-1} (mean of 3.5 cms^{-1}), which was about the same as their horizontal swimming speeds (Bowers *et al*. 1990). Measured vertical velocities should mirror the scatterers ascent (positive values) after sunset and descent (negative values) before sunrise by registering similar values with opposite signs. Vertical velocity contours for the initial 14-day June period (Fig. 2, middle panel) show very weak positive (upward) velocities (< 0.3 cms^{-1}) during daylight hours, then reversing to weakly negative (downward) throughout the dark hours, reaching a downward maximum of 0.3–0.5 cms^{-1} about 1 hour before sunrise. Though the downward velocities near sunrise are consistent with downward zooplankton migration, the reason for the downward velocities just after sunset and throughout the nighttime hours is not clear. Vertical velocities from mooring 7 exhibited the same pattern indicating it is not unique to the instrument on mooring 5.

Accuracy of ADCP vertical velocity measurements have not been explored. The manufacturer's current velocity accuracy specifications (0.5% ± 0.5 cms^{-1}) makes no distinction between the two horizontal components and the vertical component. However, vertical velocity is more accurate, by at least a factor of two, than the horizontal velocity because the angle of the beam to the vertical is more favorable (20° vs 70°) (personal communication, RD Instruments). The above error pertains only to the instrument coordinate system and does not include additional errors from compass, tilt sensors, or installation. Observed vertical velocities in the 0.3 cms^{-1} range may well be in the noise level. However, the consistent diurnal pattern in vertical velocity which matches the marked changes in backscatter cannot be dismissed.

Oscillations of the thermocline were neither of sufficient amplitude nor at appropriate frequencies to account for the observed vertical velocities. One potential problem with an ADCP in the downward-looking mode is that asymmetries in the transducer beam angles, i.e., mooring tilt, can cause a projection of the horizontal currents into the vertical component. Large mooring motions, however, are not a factor in the quiescent environment of Grand Traverse Bay. Weak currents, < 10 cms^{-1}, combined with the very taut mooring (>100 kg reserve buoyancy) constrained the pitch and roll to much less than 1° and standard deviations to < 0.2 degrees

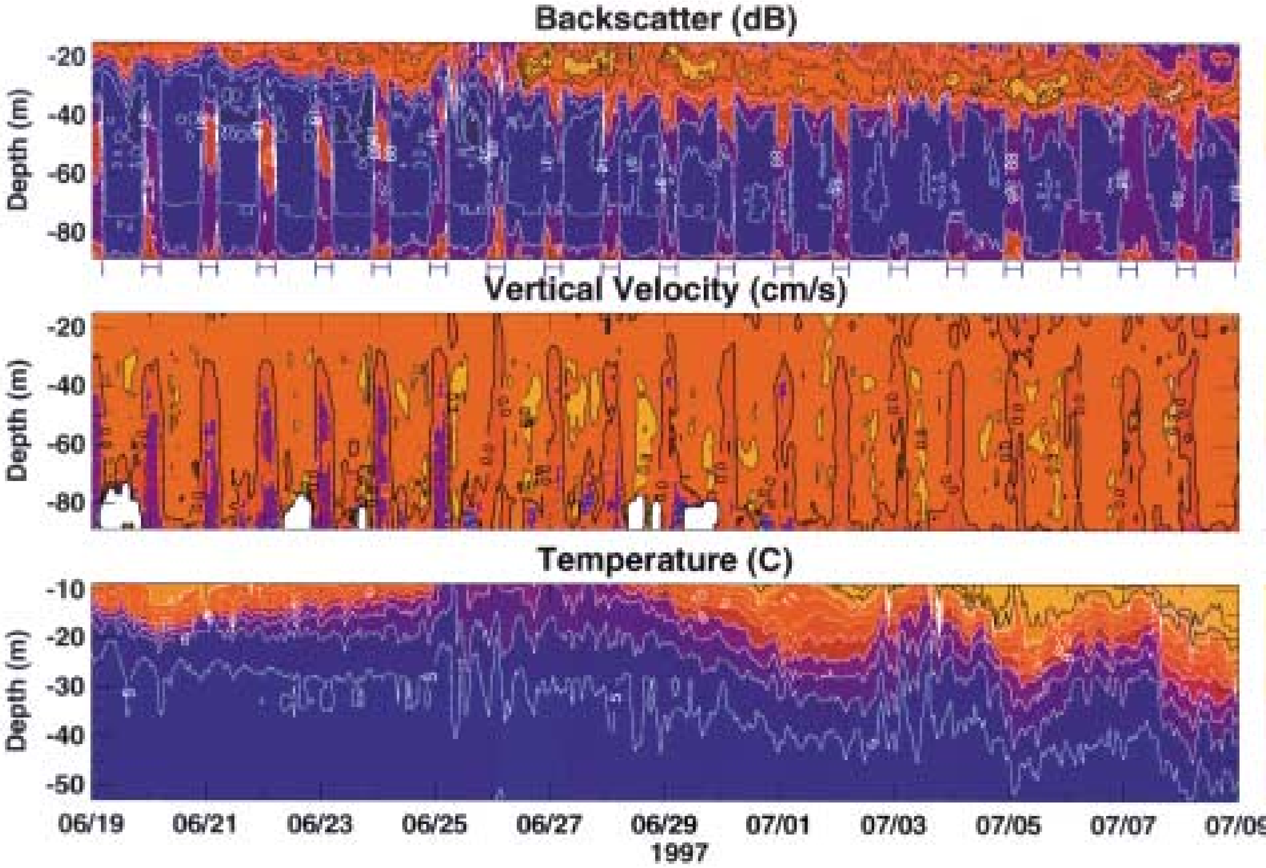

FIG. 2. Backscatter, vertical velocity, and water temperature contours, mooring 5, 18 June–8 July, 1997. Backscatter contours are 3 dB increments, vertical velocity contours are 0.3 cms^{-1} and water temperature 1°C contours. The I-beam symbols below the x-axis of the backscatter and vertical velocity contours denote the time between civil sunset and sunrise. The range of both ADCPs was limited in June by the clear water, i.e., lack of scatterers, and cold temperatures. The white areas in the middle panel indicate that the return signal did not meet the minimum quality criteria for determining a valid current velocity.

99% of the time. The internal ADCP software corrects for pitch and roll up to 20 degrees. However, Lu and Lueck (1999) reported that a 1° tilt angle bias, which is the accuracy of the sensor, may contaminate weak vertical velocities. Random mooring deviations should not produce a consistent bias in the vertical component.

Another possible contributor to the negative vertical velocity may lie in the fact that since the transmitted wavelength is close to the backscatter cross section of mysids, cross section characteristics may change when moving in opposite directions. In controlled laboratory studies, Stanton *et al.* (1998) found that echo strength from euphausiids was particularly influenced by whether the transmitted signal was near broadside (high echo return) or at an angle to the animal (much lower echo return). Sameoto *et al.* (1985) observed an instantaneous drop in backscattering strength when zooplankton were suddenly exposed to ships' lights. This decrease, up to 20 dB, was attributed to a drop in target strength resulting from the sudden coherent geometric reorientation of the zooplankton when fleeing the light. Little is know about mysid orientation in their natural environment. Robertson *et al.* (1968), during *in situ* submersible dives in Lake Michigan, observed that mysids oriented themselves into the current when on the bottom and, in a quiescent environment, those in the water column alternated between periods of swimming and periods of slow sinking. Mysids were also observed to sink with their long axis oriented vertically with either the head or caudal end upward (Robertson *et al.* 1968). Bowers *et al.* (1990) observed both active

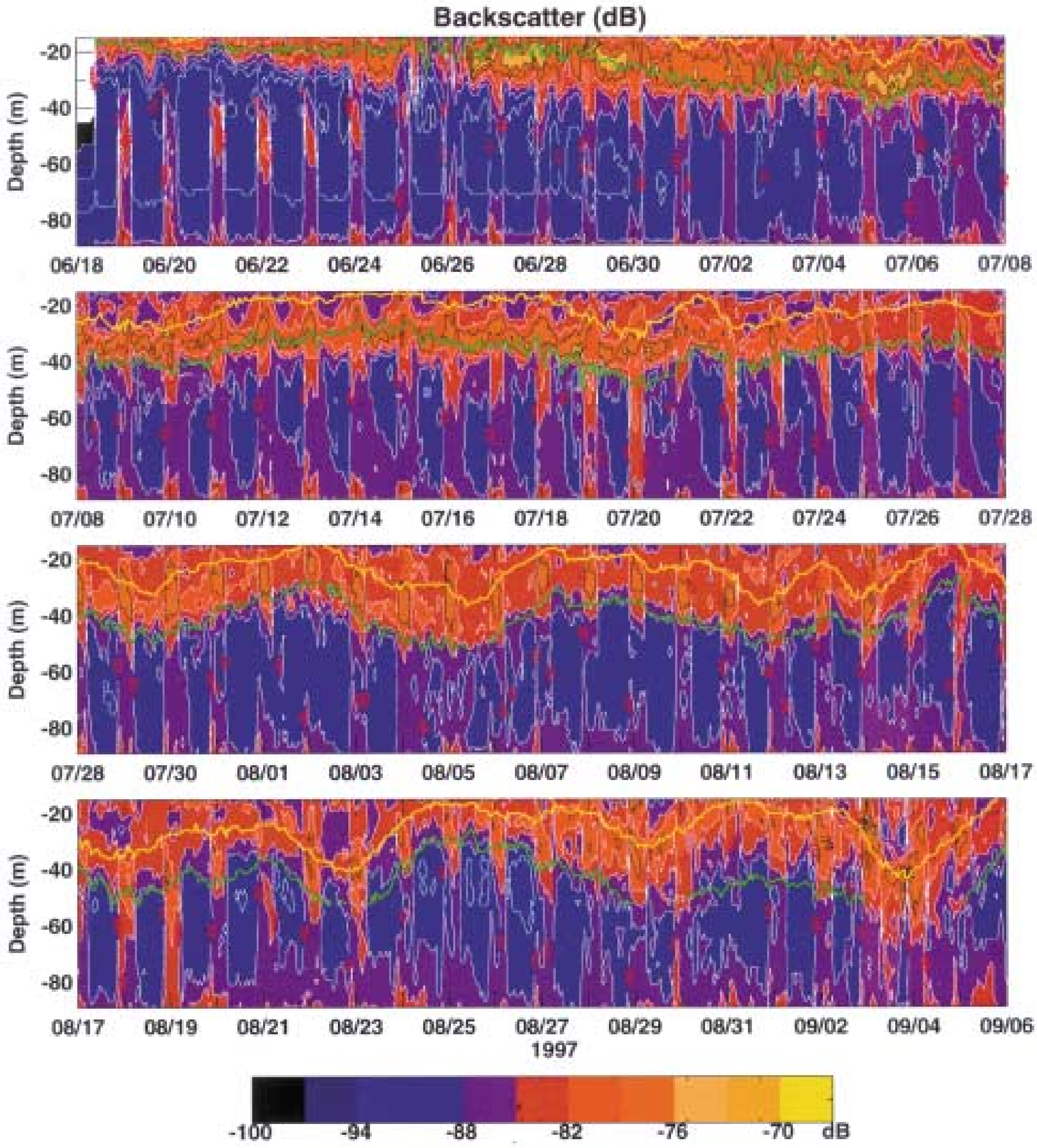

FIG. 3. Backscatter for 80 days at mooring 5. Backscatter contours are 3 dB increments. The superimposed yellow and green lines denote the depths of the 10°C and 6°C isotherms, respectively. Full moon occurred on 20 June, 20 July, and 18 August 1997.

upward and downward swimming at speeds comparable to the horizontal mean speed of 3.5 cms^{-1} and described major differences in mysid orientation during vertical migration and during typical horizontal movement during the night. Differences in the effective cross section of scatterers moving in opposite directions may produce a bias in the vertical component.

In addition to the diurnal backscatter signal, a persistent layer of high reflectivity, or sound scattering layer (SSL), was present throughout the summer (Fig. 3). The lower boundary of the 15–20-m thick layer gradually descended to about the 40 m depth during the last 2 weeks in June. Generally, the SSL was confined to water in the 6°C (superimposed green line in Fig. 3) to 10°C (yellow line) temperature range and fluctuations in depth were in step with wind-induced oscillations of the isotherms. Net tows were not made; therefore, the constituents of this scattering layer were not identified but are probably made up of many species of zooplankton and the invertebrates that feed on them. Bio-scattering layers are common in the Great Lakes; however, the strength and consistency in Grand Traverse Bay are distinctive.

Traditional zooplankton sampling is, by technique, a point measurement in time and space. Given the temporal and spatial variability of zooplankton concentrations, extrapolations of these data to characterize the status and trends of the biomass in large lakes are in question. Scatterers are Lagrangian flow indicators in the water column whose distribution is generally affected by the interactions of currents and bottom topography. The quiescent environment in Grand Traverse Bay during summer results in considerably less physically induced temporal and spatial plankton variability than in the open waters of the Great Lakes. In southern Lake Michigan, for example, storms, advection, and large internal thermal oscillations effectively redistribute zooplankton, which results in significant temporal and spatial scatterer variability (Miller *et al*. 2002). These measurements from Grand Traverse Bay demonstrate that ADCP backscatter data have potential to provide long-term monitoring of vertically migrating zooplankton species distribution, DVM characteristics, and scatterer population densities in large lakes. Verification using traditional and more sophisticated sampling methods, additional ADCP calibration, and acoustic characterization of zooplankton (e.g., Gal *et al*. 1999) are necessary for the ADCP's full potential to be realized. To echo Roe and Giffiths (1993), "ADCPs are routine instruments for oceanographers—they should become so for biologists."

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