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Vertical Distributions of Zooplankton at the Mouth of Chesapeake Bay and Calibration of Backscatter From an Acoustic Doppler Current Profiler

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**VERTICAL DISTRIBUTIONS OF ZOOPLANKTON AT THE
MOUTH OF CHESAPEAKE BAY AND CALIBRATION OF
BACKSCATTER FROM AN ACOUSTIC DOPPLER CURRENT
PROFILER**

by

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B.S. May 1997, Old Dominion University

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ABSTRACT

VERTICAL DISTRIBUTIONS OF ZOOPLANKTON AT THE MOUTH OF CHESAPEAKE BAY AND CALIBRATION OF BACKSCATTER FROM AN ACOUSTIC DOPPLER CURRENT PROFILER

Arthur Keith Jenkins
Old Dominion University, 2002
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This study investigated the physical factors influencing the vertical distribution of zooplankton at the mouth of the Chesapeake Bay and attempted to derive biological data from acoustic Doppler current profiler (ADCP) backscatter. A single site was occupied in the North Channel at the mouth of Chesapeake Bay (37° 04' N, 75° 58' W) from 17.0-19.7 November 1999. Temperature, salinity, fluorescence, light transmission, current velocity and backscatter were measured throughout the sampling period. Plankton samples were collected every hour from 3.5, 7.5, and 11.5 m.

A storm event from 17.0-17.7 November 1999, produced 10-15 m s⁻¹ northwest winds pushing two distinct fresh (24.7-30.0 psu) water-masses from up-bay across the study site, which contained relatively low abundances of zooplankton taxa. As the northwest wind subsided, salty coastal water (30.0-32.5 psu) rebounded into the study area with two strong flood tides separated by a weak ebb tide that coincided with peak abundances of dominant zooplankton taxa. Near the surface, *Lucipher faxoni*, *Sagitta* sp. and crab megalopae were more abundant on flood tide and crab zoeae more abundant on ebb tide. The distributions were generally consistent with those predicted by selective tidal stream transport models. However, we also documented flood flows approximately 80% faster than ebb flows near the bottom, and a 12-hr periodicity of zooplankton abundance similar to that of the semidiurnal tide. We were, therefore, unable to reject a purely physical mechanism for the transport of organisms into Chesapeake Bay, whereby organisms in the bottom boundary layer were differentially re-suspended by faster tidal velocities on flood tides.

We found little association between ADCP backscatter and plankton concentrations, but stronger correlations between backscatter and light transmission suggesting the backscatter was not biological in origin. Time series analysis of tidal currents and backscatter near the bottom revealed strong correlations at 6-hr intervals, suggesting resuspension of particles due to semidiurnal tidal flows. Backscatter from a single frequency echosounder such as the ADCP may only produce a coarse estimate of suspended particles in estuaries such as Chesapeake Bay.

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INTRODUCTION

Many marine species inhabit estuarine environments during at least some stage of their life histories. Such species rely on the ability to move between these environments and the coastal ocean at a certain developmental stage. These transitions may represent crucial bottlenecks that control the dynamics of marine populations (Lipcius et al. 1995; Hare et al. 1999). Estuarine-dependent fishes and invertebrates are the targets of significant commercial and recreational fisheries along the eastern and gulf coasts of the United States (Hare et al., in review). Determining the transport of zooplankton into and out of a large, productive estuary such as the Chesapeake Bay is, therefore, fundamental to any understanding of the processes generating recruitment variability and stock size in these fisheries.

The mechanisms allowing organisms to either ingress to, or egress from estuaries are poorly understood. There is some general agreement that the processes may include both passive transport by coastal currents and some behavior on the part of individual organisms (Blanton et al. 1999; Forward et al. 1999). Wind stress and gravitational circulation on the continental shelf transport organisms in both across and along-shore directions (Johnson and Hester 1989; Hare et al. 1999; Epifanio and Garvine 2001). Differential entrainment in vertically stratified residual currents, which generally show a net flow into estuaries at depth (Valle-Levinson 1998 et al.; Churchill et al. 1999), may then move organisms from nearshore coastal waters to estuarine nursery areas (Churchill et al. 1999). Negatively buoyant organisms near the Chesapeake Bay mouth will, for instance, move inshore and up-estuary in residual near-bottom flows (Valle-Levinson et al. 2001). Planktonic organisms may also be able to exert some control over their horizontal movements by making vertical migrations in regimes with vertically stratified flows. Several studies have also invoked selective tidal stream transport (STST) to explain directed up-estuary movement of planktonic organisms (Forward et al. 1999). Selective tidal stream transport may refer to any behavior at tidal frequencies. In the specific case of transport into and up estuaries, animals are thought to move up in the

The journal model used was *Estuaries*.

water column on flood tides to ride the current up-estuary and move down during ebb tides to exploit reduced current flows at the benthic boundary layer to minimize seaward movement (Forward et al. 1999). Although both buoyancy-mediated transport and STST may lead to directional transport in estuaries, few studies have been able to adequately distinguish between these two modes (Hare et al., in review).

To fully understand the interaction of physical and biological components in the water column, it is essential to have physical and biological measurements over similar spatio-temporal scales. Traditionally, plankton research has been conducted using nets that necessarily integrate horizontal distributions along the tow path (Orr 1981; Forward et al. 1999). Similarly, multiple opening and closing nets can provide vertically stratified samples, but spatial resolution in the vertical dimension (+/- 1-2 m) still does not approach that of the physical measurements (+/- 0.1 m). Plankton pumps can provide better spatial resolution, but avoidance of pump samplers by more mobile components of the zooplankton community is well documented (Rahkola et al. 1994). The decoupling of sampling scales has often proved problematic in studies designed to examine coupling of biological and physical variables in coastal and oceanic environments.

Acoustic sensing methods provide non-intrusive, surveys that can be at the same spatio-temporal resolution at which many physical oceanographic sensors operate. Sound waves in the ocean that reflect off suspended particles such as nekton and plankton, and are then received at the point of transmission are referred to as backscatter. The intensity of backscatter from a particle is dependent on the frequency used; the size and shape of the particle; and its density contrast with the surrounding medium (Stanton, 1989). Greenlaw (1979) described a relationship between acoustic backscatter intensity and zooplankton target strength (TS). Target strength, with units of decibels (dB), can be determined using:

$$TS = 10 \log_{10} (\sigma_{bs})$$

where σ_{bs} (differential backscatter cross section) is proportional to the volume of the particle (Stanton et al. 1993; Medwin and Clay 1998). The linear summation of the target strengths of all particles sonified in a certain volume of water is called the volume scattering strength (S_v) (Medwin and Clay 1998), and can be estimated for a specific

depth and time interval using the following formula derived from equation 5 in Wiebe et al. (1997):

$$S_v = 10 \log_{10} \sum (\sigma_{bs})_{dep,time,i}$$

where $(\sigma_{bs})_{dep,time,i}$ is the mean differential backscatter cross section of scatterers, i , per cubic meter at a specific depth and time. Simply, the backscatter intensity is proportional to the total volume of all particles resonified in a certain volume of water.

Theoretical considerations have shown that an echo sounder 120 - 1200 kHz may efficiently detect a range of planktonic organisms including zooplankton, fish larvae, amphipods, and euphausiids (Medwin and Clay 1998). This observation raised the possibility that the backscatter from acoustic Doppler current profilers may provide useful information concerning zooplankton distributions over the same spatio-temporal scales as the instrument recorded current velocities. In an initial test of this concept, Flagg and Smith (1989) used backscatter from a modified 307 kHz ADCP to make estimates of biomass at the edge of the New England shelf. They used net catches to calibrate the intensity of the acoustic backscatter and were able to extrapolate biomass distributions over 2.5 days to a resolution of 2 hr and 5-m depth bins. More recently, Griffiths and Diaz (1996) compared ADCP backscatter with a calibrated echo sounder, and found that estimates of zooplankton biomass from the two instruments were highly correlated. These studies clearly highlighted the potential use of backscatter from ADCP instrumentation to provide 3-dimensional estimates of zooplankton distribution patterns. Indeed a number of recent studies have used ADCP backscatter to map zooplankton in three-dimensions across large physical features such as gyres, mesoscale eddies, and pack ice (Ashjian et al. 1994; Flagg et al. 1994; Zimmerman and Biggs 1999; Zhou et al. 1994).

Although the use of ADCP backscatter to estimate zooplankton biomass in oceanic waters has been well established, it is not clear if the same information may be available from ADCPs moored in estuarine settings. In particular, concerns have been raised that backscatter in estuarine and near-coastal waters may be dominated by non-biological material. For instance, Wiebe et al. (1997) suggested that 0.2 mm diameter sand grains in concentrations of $1 \times 10^6 \text{ m}^{-3}$ might cause an echo comparable to the scattering from zooplankton swarms. They found that backscatter from a 420 kHz echo

sonder on Georges Bank was on occasion dominated by suspended sand. Barans et al. (1997) used multiple frequencies from 265 kHz to 3 MHz in a bioacoustic survey in an estuary along the South Carolina coast and reported scattering dominated by sand on the 1.1 and 3 MHz channels. Significant scattering may also be caused by plant material (Bozzano et al. 1998) or turbulence (Stanton et al. 1994b), both of which are likely to be high in locations of high energy and high primary productivity such as estuaries. Verification of a predictive relationship between plankton biomass and ADCP backscatter in estuarine systems is, therefore, necessary before these data can be used in any routine manner.

The aim of the research described here was two-fold. First, we wanted to provide a high-resolution description of the macrozooplankton community present in the North Channel of the Chesapeake Bay and attempt to distinguish the physical events influencing their concentrations. Second, we attempted to establish a relationship between ADCP backscatter and some measure of plankton biomass. In the absence of a significant relationship between the acoustic backscatter and the biological samples, we wanted to establish other possible causes for the backscatter signal such as sediment resuspended by tidal currents.

METHODS

STUDY SITE

The study site was located at 37° 04' N, 75° 58' W, at the mouth of the Chesapeake Bay approximately 1.5 km south of Fisherman's Island National Wildlife Refuge, Virginia. The ship was at anchor during sample collection over the North Channel from 16 November 1999 at 2300 UTC until 19 November 1999 at 1600 UTC. The axis of the North Channel runs from northwest to southeast and is contained by Smith Inlet Shoal and Fisherman's Island to the northeast, and Six-Meters Shoal to the southwest. Water depth at the site is approximately 14 m and current flow is influenced by wind, tidal, and density-driven currents (Valle-Levinson 1998 et al.).

SAMPLE COLLECTION

Plankton samples were collected with 1-m² x 8 m long channel nets with 950 µm nylon mesh. A set of three channel nets, equipped with General Oceanic flow meters with low flow rotors, were fished at 3.5, 7.5, and 11.5 m on center from a lead line held vertically in the water. Channel nets were changed and emptied every hour into labeled buckets to be presorted and preserved. Samples were strained through a sieve and samples that contained large numbers of ctenophores were partially digested with bleach. Samples deemed too large to preserve in their entirety were split volumetrically aboard the vessel and a fraction was preserved. Samples were placed in 1 L jars and preserved in 95% ethanol. Ethanol was changed in samples approximately 24-hr after initial preservation.

A SeaBird SBE-25 CTD (Conductivity-Temperature-Depth) equipped with a fluorometer and a light transmissometer was cast every 30-min to obtain vertical profiles of temperature, salinity, fluorescence, and light transmission. The profile values were derived and depth bin averaged every 0.5 m by SeaBird's SeaSoft software package. Wind speed and direction were obtained from a National Oceanographic and Atmospheric Administration (NOAA) weather station located approximately 12 km southwest of the sample site on the North Island of the Chesapeake Bay Bridge Tunnel at 36° 59' N, 76° 06' W.

Current flows and backscatter were profiled throughout the duration of the experiment with a downward-facing RD Instruments 614.4 kHz Broadband ADCP, mounted in a towed-body. The instrument assembly was attached forward of the net array, and because the ship was allowed to swing on its bow anchor, the ADCP sampled the water column before the nets disturbed the water flow. The instrument recorded data from 1 m below the surface to the bottom in 0.5-m depth bins, and the signal was averaged into 20-s ensembles.

Data from a second upward-facing RD Instruments 614.4 kHz Broadband ADCP, mounted on the bottom was available from day 16.9-18.6 November 1999. The instrument was moored on the bottom approximately 100 m from the study site in the North Channel. The ADCP averaged and recorded in 0.5-m depth bins from 0.5 m from the transducers' face to the surface every 15 min.

SAMPLE PROCESSING

Samples were poured into a 500 μm sieve, rinsed with water, and zooplankton sorted from the plant material. The samples were then split into volumetrically equivalent halves using a Folsom plankton splitter until the approximate number of animals in the subsamples totaled 400 by visual estimate. Dominant organisms were identified to genus or species and uncommon organisms were identified to the lowest taxonomic level but often only to order or family (Gosner 1971; Williams 1984). The length of the longest and shortest organism for each species that comprised greater than 5% of each subsample was determined to the nearest 0.5-mm using mechanical calipers. Ichthyoplankton were enumerated separately and data were provided on concentrations of dominant species for different sizes and stages (Hare et al., in preparation).

CALCULATIONS

Data from zooplankton enumerations was used to calculate the concentration (m^{-3}) of organisms from the number of field splits, number of Folsom splits, and the volume filtered by the net. Zooplankton concentrations from missing samples were linearly interpolated from adjacent depth and time bins for use in contour plots. Zooplankton and ichthyoplankton concentrations were log transformed ($\log_{10}(x + 1)$) for comparison with ADCP backscatter.

The mean volume for each dominant crustacean species was estimated using the relationship:

$$\text{volume (mm}^3\text{)} = 0.130 + 0.019 * \text{length (mm)}^3$$

where length is the mean of the shortest and longest organism in all subsamples (Flagg and Smith, 1989). The volume for *Sagitta* sp. was estimated using the simple geometric relationship for the volume of a cylinder:

$$\text{volume (mm}^3\text{)} = \pi * \text{radius (mm)}^2 * \text{length (mm)}$$

where the radius is $0.10 * \text{length}$. From this data, the volume concentration ($\text{mm}^3 \text{m}^{-3}$) of zooplankton in each sample was calculated.

Mean zooplankton concentrations were calculated for flood tide, ebb tide, day, and night for each depth. Flood and ebb tide were judged by averaging the ADCP east-west flow during each fishing time and depth, with negative values (west) representing flood flow and positive values (east) representing ebb flow. Nets that were fished concurrent with mean east-west currents less than 5 cm s^{-1} , slack water, were dropped from the calculations. Night and day samples were separated by sunrise and sunset, and nets that were fished during sunrise or sunset were eliminated from the analysis. Auto and cross-correlations were performed on time series of dominant zooplankton taxa and east-west (tidal) currents at 11.5 m to illustrate whether zooplankton abundances were fluctuating at tidal frequencies.

Relative backscatter (RBS) from the ADCP was processed to account for transmission loss from radial spreading and sound attenuation. A formula for the correction was provided by Deines (1999):

$$C_v = C + 20 * \log_{10}(R) - L_{DBM} - P_{DBW} + 2\alpha R + K_c (E - E_r)$$

where C_v is proportional to $10\log_{10}(\text{scatterer concentration})$, C is a system constant that incorporates several system parameters (dB), L_{DBM} is $10 * \log_{10}(\text{transmit pulse length (m)})$, P_{DBW} is $10 * \log_{10}(\text{transmit power (watts)})$, $2\alpha R$ is the two-way sound attenuation to the depth cell, K_c is the received signal strength indicator scale factor (dimensionless), E is the echo intensity (counts) for each time and depth cell, and E_r is the echo intensity reference level (counts). Values for C , L_{DBM} , P_{DBW} , and E_r did not change during the experiment and therefore these constant parameters were dropped from the equation to yield:

$$RCBS \text{ (dB)} = 20\log_{10}(R) + 2\alpha R + RBS$$

where RBS is the relative backscatter from each time and depth bin and is equal to $K_c * E$, and all other parameters are as above. This equation is very similar to the equation for range correction given in Flagg and Smith (1989). R can be calculated using:

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

where B is the blank after transmit (m), L is the transmit pulse length (m), D is the depth cell length (m), N is the depth cell number (dimensionless), θ is the slant of the transducers (degrees), c' is the average sound speed from the transducer to the depth cell ($m s^{-1}$), and c_1 is the speed of sound used by the instrument ($m s^{-1}$) (Deines, 1999). The value for c' for each time and depth cell was calculated by first using:

$$c = 1449 + 4.6 * T - 0.55 * T^2 + 1.4 * (S - 35) + 0.017 * d$$

where c is the speed of sound within each depth and time bin ($m sec^{-1}$), T is the temperature ($^{\circ}C$), S is the salinity (psu), and d is the depth (m). Temperature and salinity data for this calculation were taken from the CTD data nearest in time to the relevant backscatter data. The ratio c'/c_1 was invariably found to be very close to 1.0, and because it is the only factor in the equation used to calculate R that varied with time, the term was dropped. Values calculated for R using the remainder of the formula were very close to the bin depth recorded by the ADCP, and therefore the ADCP depth vector was used in place of R. Values for $2\alpha R$ for each depth and time bin were found by first calculating the absorption for each depth cell α_n :

$$\alpha_n = (2 * \alpha_p * D) / \cos\theta$$

Then the value $2\alpha R$ can be calculated using:

$$2\alpha R = (2 * \alpha_p * B) / \cos\theta + \sum \alpha_n$$

where α_p is the sound absorption at the profiler, $\sum \alpha_n$ is the summation of the absorption from the first depth cell to the range depth cell, and all other parameters are as defined above (Deines, 1999). Values for α are given in Table IV of Francois and Garrison (1982) for a range of temperatures and either 30 or 35psu. It was found that temperature and salinity did not vary enough during the sampling to have a significant impact on the sound absorption, and therefore a mean value for α was used throughout.

Mean values for RCBS were calculated for comparison with other factors. First, the mean RCBS among all four beams was calculated. The RCBS data were then averaged during the time and depth ranges of each individual net to compare with the zooplankton data. To correlate RCBS with light transmission and chlorophyll, the backscatter data were averaged from five minutes on either side of the CTD cast for each of the 21 depth bins. To compare the backscatter from the upward and downward-facing ADCPs, the data from the downward-facing ADCP was averaged into 15-min bins concurrent with the 15-min bins of the upward-facing instrument. To make the correlations between RCBS and light transmission more intuitive, reciprocal light transmission was calculated by subtracting the value for light transmission (%) at each time/depth from 100%. Auto and cross-correlations were performed on time series of RCBS and east-west (tidal) currents at 11.5 m to look for patterns of backscatter at tidal frequencies.

RESULTS

SAMPLE COLLECTION

The study site was occupied between 16 November 1999 at 2300 UTC and 19 November 1999 at 1600 UTC. A total of 60-hr of ADCP profiles and 50-hr of CTD data was recorded. Channel net samples totaled 152, with 7.5 m net samples available only on even numbered sets after the sixth set. Nets were fished for 40-80 min and filtered 46.1-2847 m³ of water.

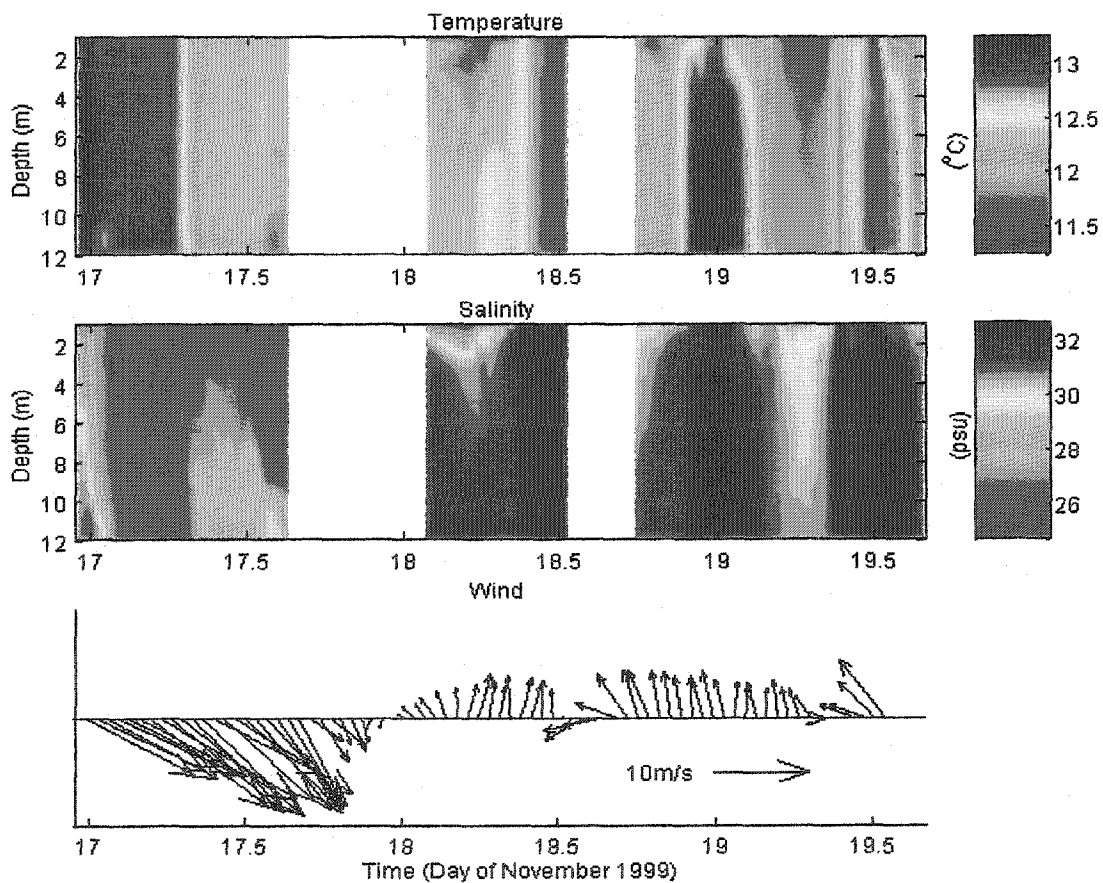


Fig. 1. Temperature ($^{\circ}\text{C}$), salinity (psu), and wind (m s^{-1}) profiles at the study site, 17-19 November 1999. Temperature and salinity measured by CTD casts every 30 minutes. White areas of temperature and salinity plots indicate no data available during these times. Wind arrows based on data reported by the NOAA weather station located nearby the study site on the Chesapeake Bay Bridge Tunnel.

PHYSICAL ENVIRONMENT

Temperature ranged from 11.24-13.25°C and salinity ranged from 24.73-32.57 psu during the sampling period (Fig. 1). Vertical stratification of the water column was minimal compared with temporal variability averaged throughout the water column. During day 17.0-17.7 November 1999, strong ($10-15 \text{ m s}^{-1}$) winds were experienced from the northwest (Fig. 1). Coincidental with this wind event, two distinct water-masses, warm-fresh ($12.5-13.2^\circ\text{C}$ and $24.7-30.0$ psu) and cool-fresh ($11.2-12.5^\circ\text{C}$ and $24.7-30$ psu), were observed at the study site (Fig. 2). Winds were from the south through southeast and light ($<5 \text{ m s}^{-1}$) for most of the remainder of the study period, which allowed saltier coastal water to rebound into the study site. This salty water-mass could be further divided into two water-masses based on its bimodal temperature distribution (Fig. 1). These two water-masses were warm-salty ($12.5-13.2^\circ\text{C}$ and $31.5-32.5$ psu) and cool-salty ($11.2-12.5^\circ\text{C}$ and $30.0-32.5$ psu), coincident with the flood and ebb tide respectively. Beginning at day 19.5, a southwest wind began to build to 8 m s^{-1} (Fig. 1).

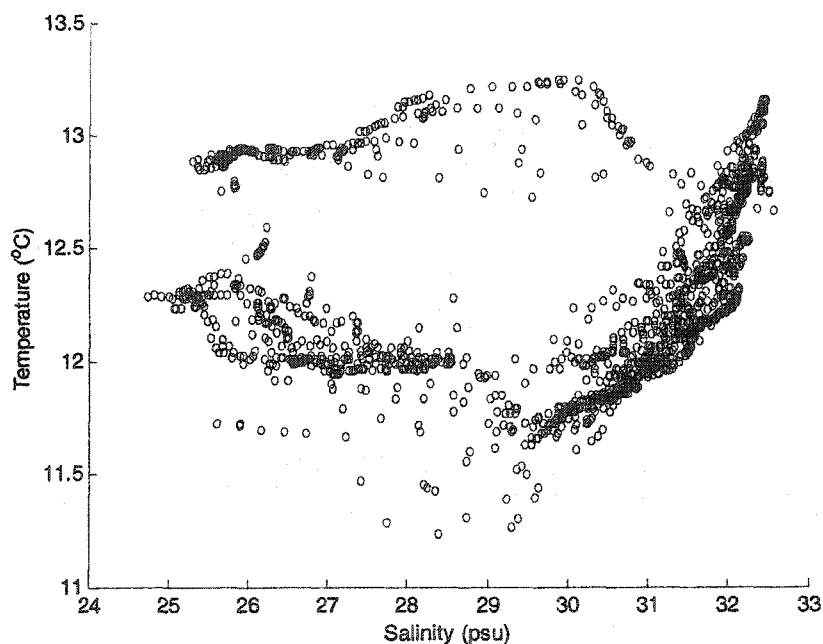


Fig. 2. The interaction of temperature and salinity at the study site, 17-19 November 1999. (n = 2323)

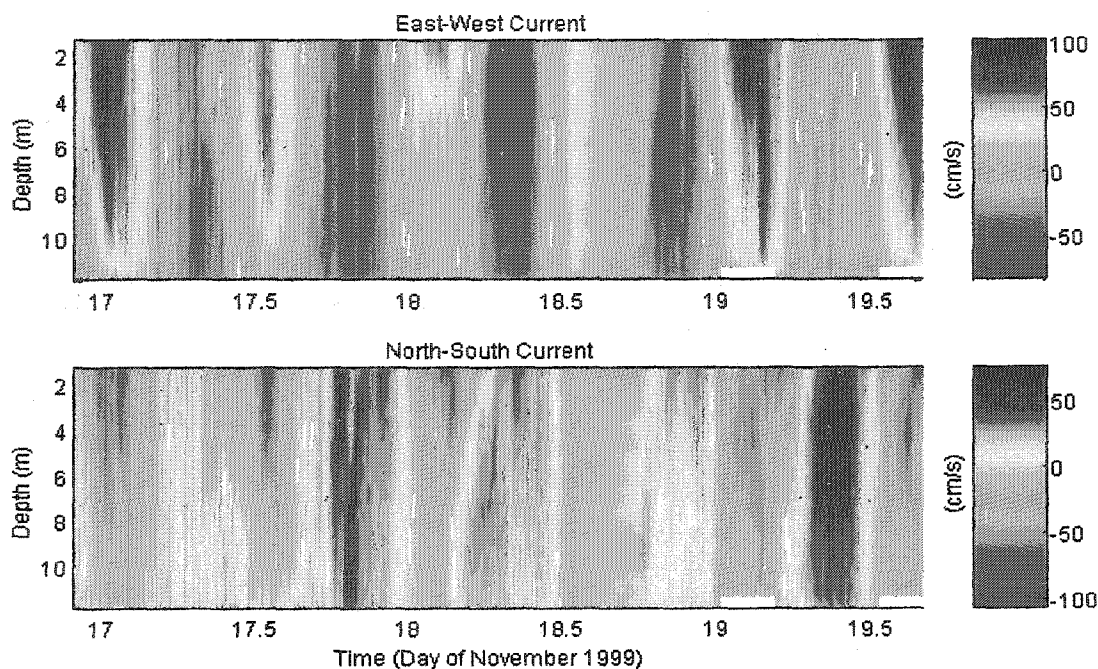


Fig. 3. East-West and North-South currents at the study site, 17-19 November 1999. Negative (-) values on color-axes represent West and South flow respectively.

Overall, ebb tides flowed towards the southeast along the axis of the channel and reached a maximum of 118.0 cm s^{-1} near the surface and 61.1 cm s^{-1} near the bottom. Flood tides generally flowed towards the northwest and reached a maximum of 82.9 and 79.7 cm s^{-1} near the surface and bottom respectively. Based on current vectors averaged over the sampling period, the residual flow was out of the estuary near the surface, with ebb flows 25% greater than flood, and into the estuary near the bottom, with flood flows 81% greater than ebb.

Currents were driven primarily by the semidiurnal tide along the North Channel, the wind, and the resulting density gradient. The flood tide observed during the initial northwest wind event was weak, greatly diminished near the surface, and flowed towards the west (Fig. 3). After the subsidence of the northwest wind, the coastal water rebounded into the area during day 17.7-18.5, with two strong flood tides separated by a weak ebb tide that was greatly diminished near the bottom. Near the end of the period of

measurements, the flood flow centered on day 19.4, had a strong northerly component, especially near the surface, concurrent with the building of a southeast wind.

TABLE 1. Abundance and frequency of all taxa caught at the study site, 17-19 November 1999. Mean, standard error, minimum, and maximum for taxa are based on concentrations (m^{-3}) in each net. Frequency is the number of nets the taxon occurred in out of the total number of nets ($n = 151$).

Taxon	Mean	Standard Error	Minimum	Maximum	Frequency (%)
<i>Mysidopsis bigelowi</i>	38.0	9.5	0	1171	93
<i>Lucipher faxoni</i>	3.1	0.26	0	30.4	97
<i>Sagitta sp.</i>	2.7	0.27	0	26.7	75
<i>Labidocera aestiva</i>	1.6	0.031	0	36.5	97
<i>Neomysis americana</i>	0.97	0.024	0	47.2	58
Crab megalope	0.31	0.010	0	2.8	79
Cumaceans	0.14	0.0072	0	5.6	51
Crab zoea	0.12	0.24	0	1.0	73
Gammarid amphipods	0.092	0.018	0	1.9	69
Shrimp zoea	0.060	0.0017	0	2.8	38
<i>Amphioxus sp.</i>	0.052	0.010	0	7.0	9
Benthic isopod	0.037	0.0014	0	0.97	26
<i>Acetes americanus carolinae</i>	0.033	0.00026	0	1.0	37
Calanoid copepods	0.012	0.000091	0	0.50	32
Cymothid isopods	0.010	0.037	0	0.52	27
<i>Palomonetes sp.</i>	0.010	0.28	0	0.26	24
Crab post larvae	0.0077	0.0011	0	0.14	22
Caprellid amphipods	0.0067	0.0027	0	0.27	27
Pteropods	0.0063	0.0023	0	0.64	2
<i>Squilla sp.</i>	0.0011	0.0051	0	0.036	6
<i>Loligo spp.</i>	0.00037	0.0050	0	0.018	5

ZOOPLANKTON

Twenty-two zooplankton taxa were identified from a total of 151 channel net samples (Table 1), of which, 148 samples coincided with complete physical and acoustic records. Total zooplankton concentrations summing all taxa for each individual net, ranged from 0.0044 to 1243 m⁻³. The mysid shrimp *Mysidopsis bigelowi* was over an order of magnitude more abundant than any other taxa, with a maximum concentration of 1171 m⁻³ and mean concentration of 38.0 m⁻³, and was found in 93% of the samples. The penaeid shrimp *Lucipher faxoni* and the copepod *Labidocera aestiva* were found in 97% of the samples, with mean concentrations of 3.1 and 1.6 m⁻³ respectively. Chaetognaths (*Sagitta* sp.), *Neomysis americana*, crab megalopae, cumaceans, and crab zoeae were all found in greater than 50% of the samples and had mean concentrations greater than 0.10 m⁻³.

Dominant zooplankton taxa were not randomly distributed throughout the four identified water-masses (Fig. 4). The two fresh water-masses, pushed out of the Chesapeake Bay by the prevailing northwest wind during the first part of the sampling period, contained the lowest abundances of zooplankton overall. The warm-fresh water, the first water-mass encountered during the study, had the lowest zooplankton concentrations of the four water-masses, with populations consisting of relatively few *M. bigelowi*, *L. aestiva*, crab megalopae, and crab zoeae. Only *M. bigelowi*, crab megalopae, and crab zoeae were found in any numbers in the cool-fresh water-mass. Concentrations of *M. bigelowi*, *L. faxoni*, and *L. aestiva* were higher in the cool-salt rather than in the warm-salt water-mass. Chaetognaths (*Sagitta* sp.), crab megalopae, and crab zoeae were approximately equally distributed in both salty water-masses.

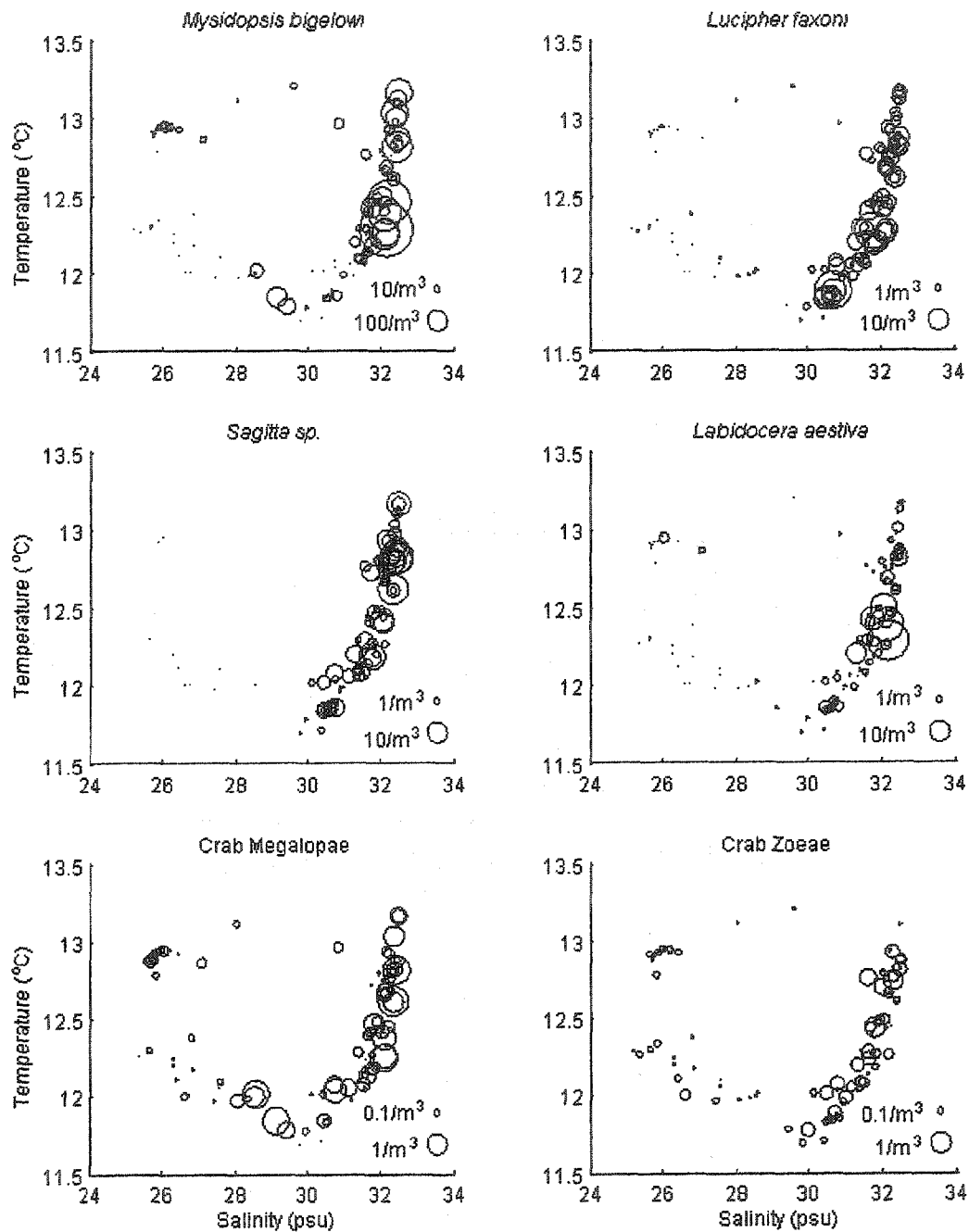


Fig. 4. Dominant zooplankton taxa in temperature-salinity space caught at the study site, 17-19 November 1999. Bubble size represents concentration (m^{-3}); notice scale varies from plot to plot. Temperature and salinities are based on average of all CTD measurements encompassed by the net's fishing time and depth ($n = 148$).

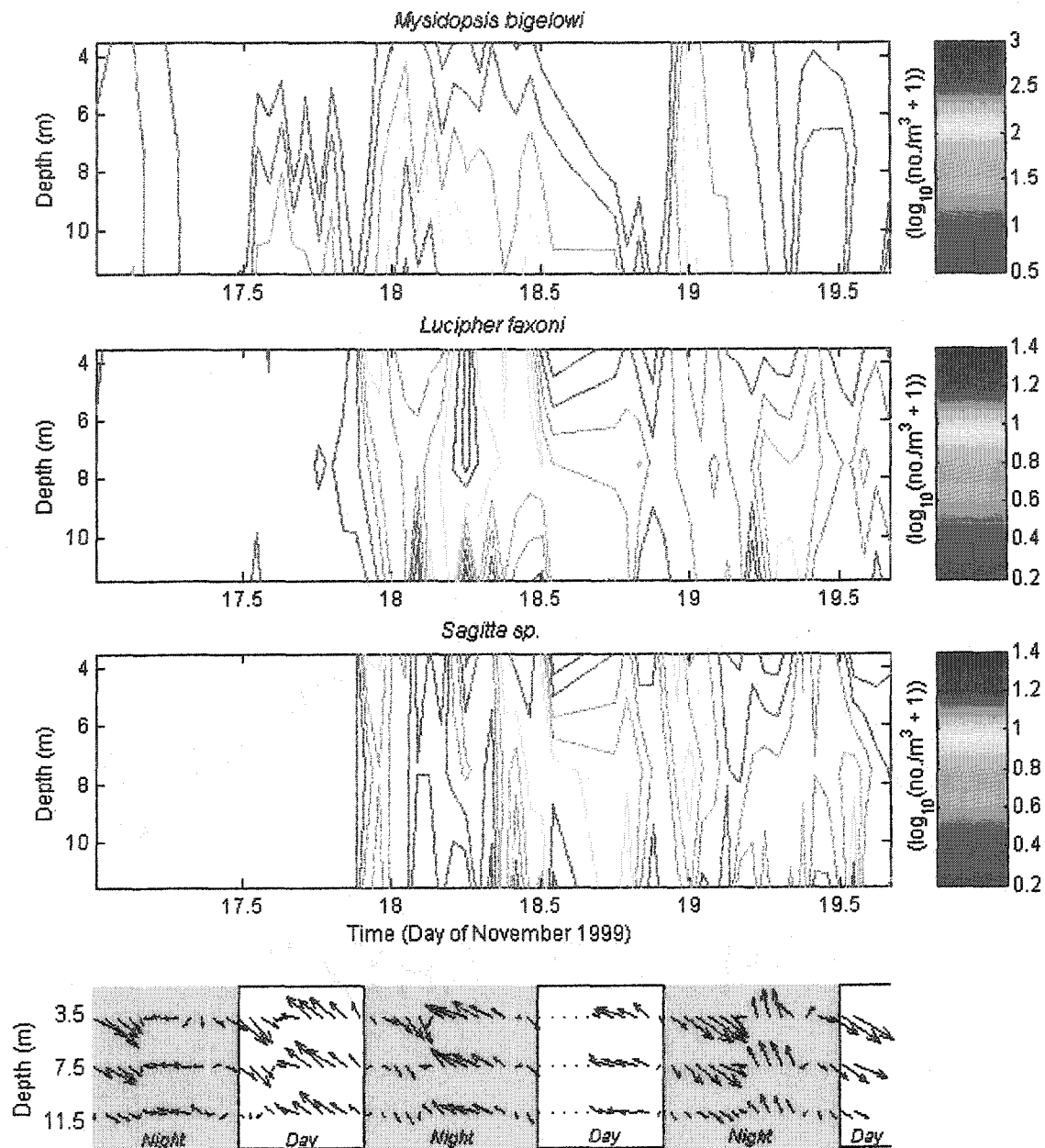


Fig. 5. Contour plots of log transformed ($\log_{10}(x + 1)$) *Mysidopsis bigelowi*, *Lucifer faxoni*, and *Sagitta sp.* concentrations (m^{-3}) at the study site, 17-19 November 1999. Note that color-axes are scaled differently among the plots. Bottom plot shows light cycle and current vectors averaged over each nets fishing time and depth. The longest current vectors are equal to approx. 95 cm s^{-1} (up represents north).

The rebounding of the coastal water after the weakening of the strong northwest wind (day 17.5-18.5 November 1999) brought the highest overall abundance of zooplankton, with many taxa reaching their maximum concentrations of this study (Fig. 5 and 6). There was an initial pulse of *M. bigelowi* and crab megalopae near the bottom on day 17.5-17.8, coincident with the strongest flood tide of the sampling period. During night on day 18.0-18.5, *M. bigelowi*, *L. aestiva*, and crab megalopae reached their highest concentrations near the bottom and *L. faxoni* reached their highest numbers near the surface, coincident with the weakest ebb tide observed in this study and another swift flood tide. A smaller peak of crab megalopae was seen near the surface on day 18.4-18.5 during night and slack water following strong flood flow. Before sunrise at day 18.4, *Sagitta* sp. density peaked near the surface, but then peaked near the bottom after sunrise on day 18.6. *Sagitta* sp. peaked again during daytime, ebb flow on day 19.5-19.6. Crab zoeae exhibited their maximum abundances near the surface on an ebb tide during the daytime on day 19.5-19.7, coincident with a strong ebb tide and a building southwest wind.

Overall, *M. bigelowi* and *L. aestiva* had significantly higher concentrations at 11.5 m than at other depths (Figs. 5 and 6). Crab megalopae also had their highest numbers at 11.5 m, but also had significant numbers at 7.5 and 3.5 m, unlike *M. bigelowi* and *L. aestiva*. Crab zoeae and *L. faxoni* had slightly higher abundances at 3.5 and 7.5 m respectively when compared with other depths and *Sagitta* sp. showed no clear tendency for depth.

Depth dependent distributions of the dominant zooplankton taxa were influenced by both time of day and tidal state. There were 73 night and 60 day samples collected, with 15 net samples dropped from this analysis due to being fished during sunrise or sunset. Similarly, there were a total of 56 and 74 nets fished during ebb and flood flow respectively, with 18 nets dropped due to being fished at slack water, defined when the mean east-west current vector at the depth and time fished was $<5 \text{ cm s}^{-1}$ according to the ADCP records. Overall, there were significant contrasts within four dominant taxa due to differences in zooplankton abundances during the flood versus ebb flow and also four significant contrasts due to day versus night abundances (Fig. 7). All significant

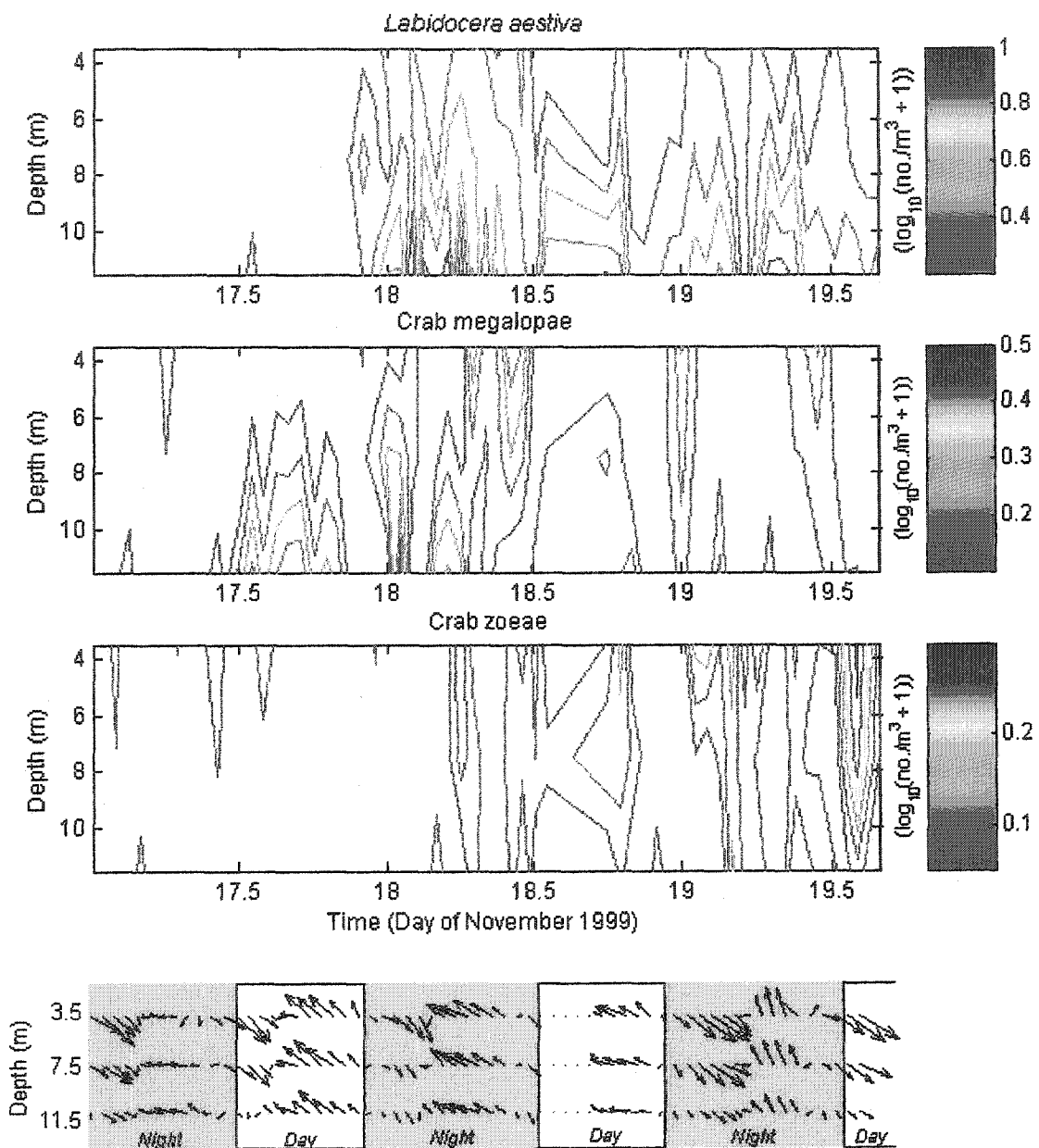


Fig. 6. Contour plots of log transformed ($\log_{10}(x + 1)$) *Labidocera aestiva*, crab megalopae, and crab zoeae concentrations (m^{-3}) at the study site, 17-19 November 1999. Note that color-axes are scaled differently among the plots. Bottom plot shows light cycle and current vectors averaged over each nets fishing time and depth. The longest current vectors are equal to approx. 95 cm s^{-1} (up represents north).

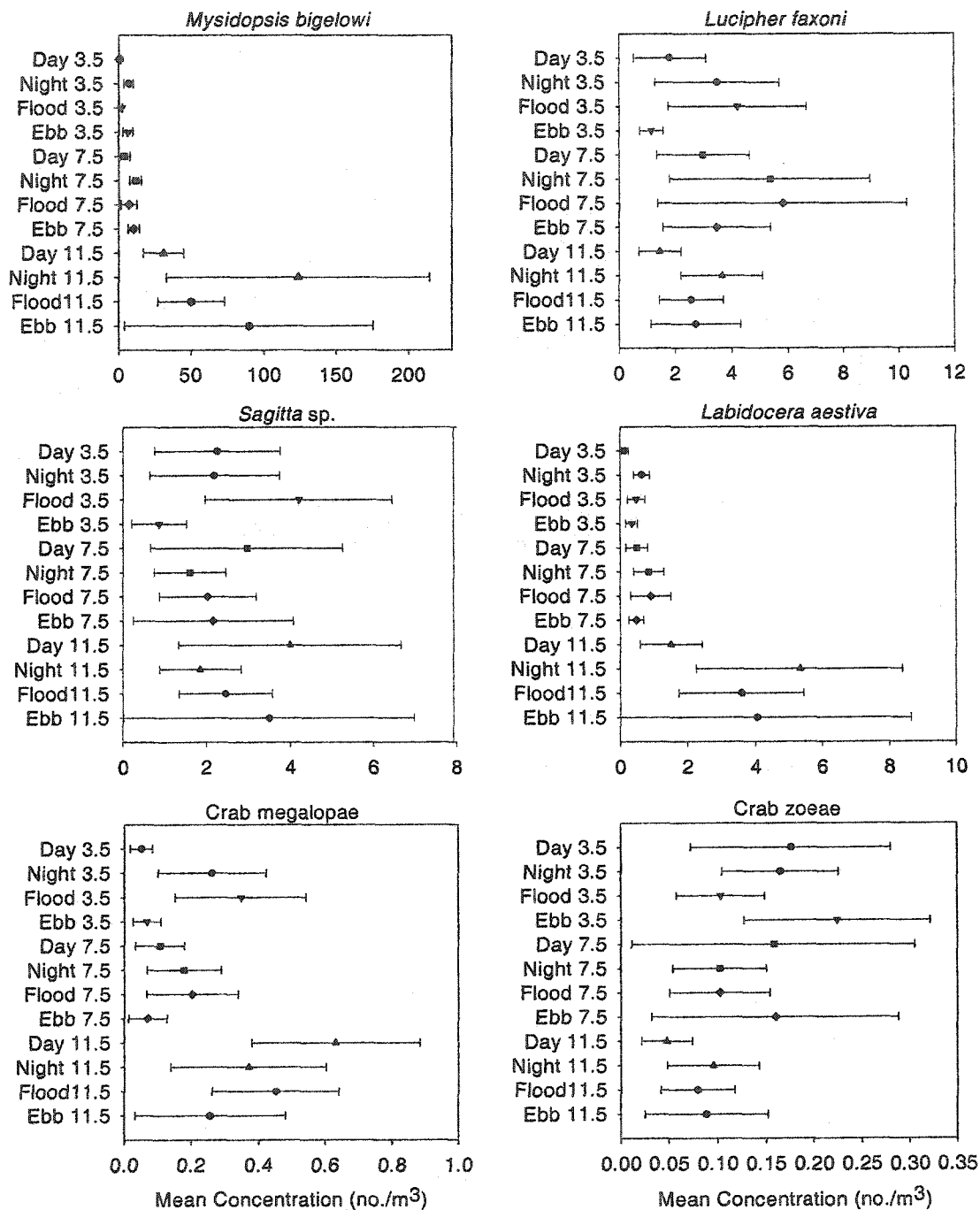


Fig. 7. Mean concentrations (m⁻³) with 95% confidence limits for the six dominant species at different light (day/night) and tidal (flood/ebb) stages caught at the study site, 17-19 November 1999. Note that the x-axes are scaled differently among the plots.

flood-ebb contrasts happened at 3.5 m but day-night contrasts happened throughout the water column. *Mysidopsis bigelowi* had its highest abundances during night at all depths and had slightly higher abundances during ebb tides at 3.5 and 11.5 m. Similarly, *L. faxoni* and *L. aestiva* had their highest numbers at night at all depths, but had higher concentrations during flood tides at 7.5 and 3.5 m especially for *L. faxoni*. Crab megalopae and *Sagitta* sp. also had significantly higher densities at 3.5 m during flood tides. Crab megalopae had slightly higher numbers at 7.5 and 11.5 m during flood tides and showed diel periodicity with more caught at 3.5 m during the hours of darkness, but higher densities at 11.5 m during the light. Crab zoeae had higher concentrations at ebb rather than flood tide at 3.5 and 7.5 m, and had slightly higher concentrations during the day at 7.5 m and during the night at 11.5 m.

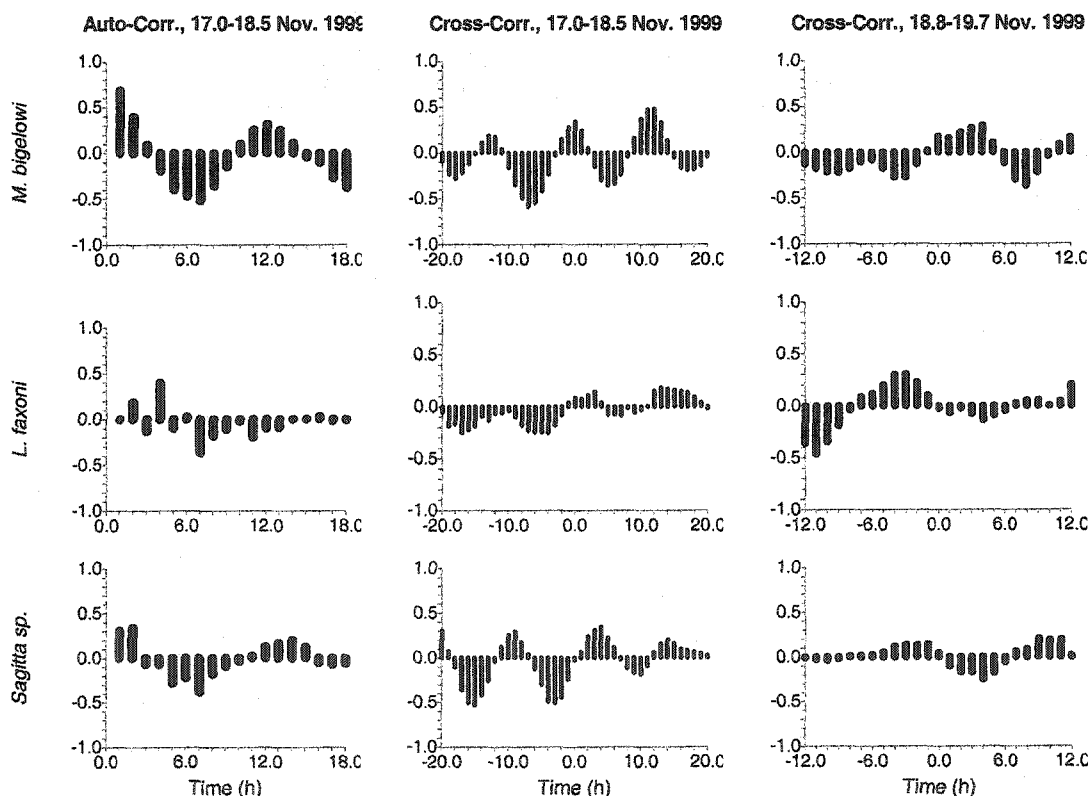


Fig. 8. Auto-correlation of log transformed *M. bigelowi*, *L. faxoni*, and *Sagitta* sp. concentrations for days 17.0-18.5 November 1999 and cross-correlations of same three taxa versus east-west (tidal) flow for days 17.0-18.5 (center) and 18.8-19.7 (right) November 1999.

The east-west flow recorded by the ADCP was compared to the log transformed concentration of different taxa at 11.5 m using auto and cross-correlations for days 17.0-18.5 and 18.8-19.7 November 1999, encompassing 37 and 22 hrs of observations respectively (Fig. 8 and 9). During day 17.0-18.5, concentrations of *M. bigelowi* exhibited a strong 12-hr periodicity, with auto-correlation coefficients approaching 0.8, and strong, zero-lag cross-correlations versus tidal flow, with coefficients reaching approx. 0.6. However, *M. bigelowi* showed weaker periodicity during day 18.8-19.7, with cross-correlation coefficients exceeding 0.4. Crab megalopae and *Sagitta* sp. demonstrated periodicity at tidal frequencies with auto-correlation coefficients approaching 0.4 and 0.5 respectively during day 17.0-18.5. Cross-correlations of crab

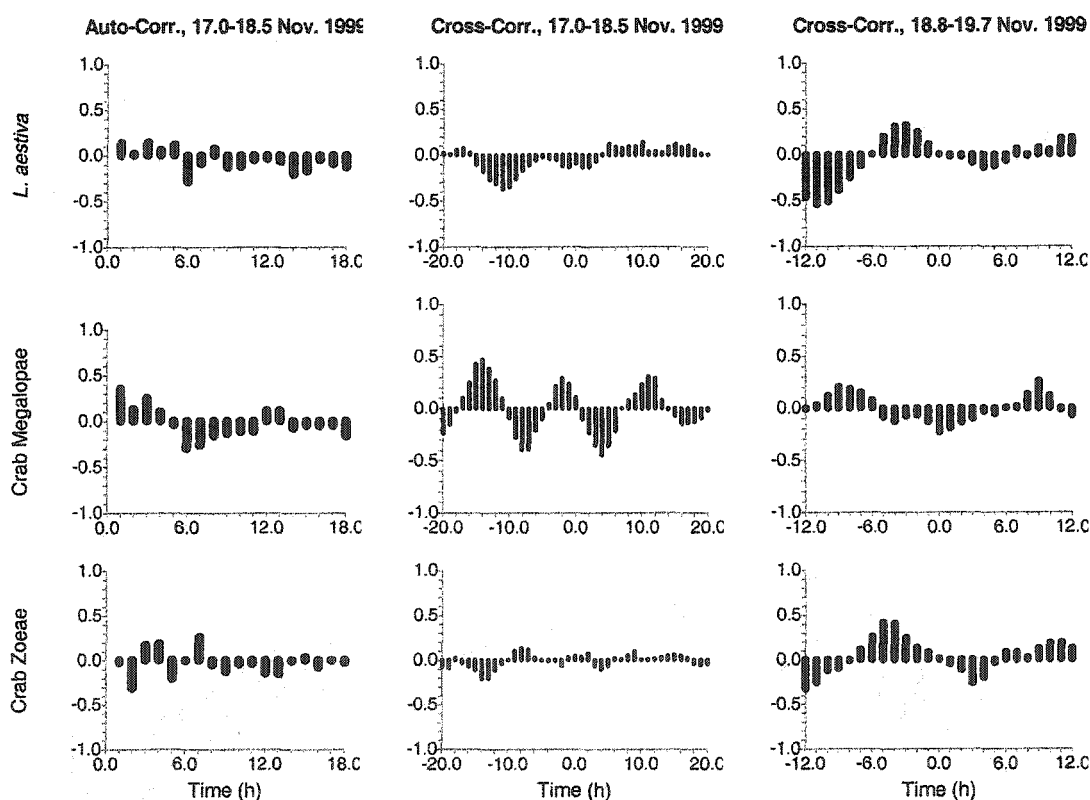


Fig. 9. Auto-correlation of log transformed *L. aestiva*, crab megalopae, and crab zoeae concentrations for days 17.0-18.5 November 1999 and cross-correlations of same three taxa versus east-west (tidal) flow for days 17.0-18.5 (center) and 18.8-19.7 (right) November 1999.

megalopae and *Sagitta* sp. concentrations versus tidal oriented (east-west) flow produced absolute coefficients of 0.5 and 0.6 respectively exhibiting a semidiurnal cycle approx. 3-hr out of phase with tidal flow during day 17.0-18.5. During day 18.8-19.7, crab megalopae and *Sagitta* sp. maximum cross-correlation coefficients were both only 0.3. *Sagitta* sp. demonstrated a weak semidiurnal pattern; and crab megalopae showed a strong pattern, but at an approx. 18-h period. Auto and cross-correlations for *L. faxoni*, *L. aestiva*, and crab zoeae did not reveal any periodicity at semidiurnal tidal frequencies or any significant cross-correlations with east-west flow during day 17.0-18.5. During day 18.8-19.7, *L. faxoni*, *L. aestiva*, and crab zoeae had cross-correlation coefficients of 0.6, 0.6, and 0.5 respectively. Semidiurnal periodicity was more defined in *L. aestiva* and crab zoeae than in *L. faxoni*, and peak concentrations were shifted 3-hr out of phase with peak tidal flow.

ADCP BACKSCATTER

Relative backscatter from the ADCP was range corrected, resulting in greater amplification of the backscatter intensity with greater distance from the transducers (Fig. 10). The range correction also spread the range of backscatter from 59.3-117.5 dB for RBS to 62.1-142.4 dB for RCBS. Visually, the plots of RCBS from downward and upward-facing ADCPs are very similar, with the exception of above 2.0 m where there

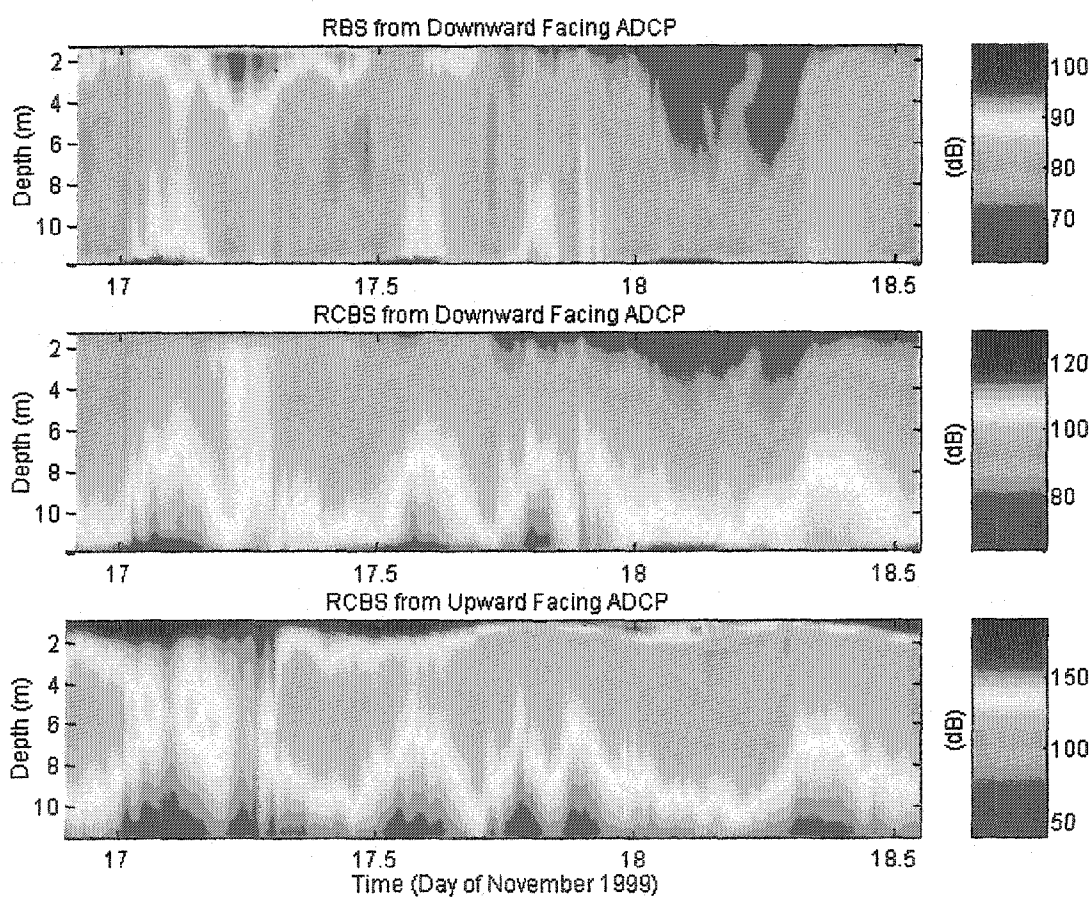


Fig. 10. Relative backscatter from a downward-facing ADCP, RCBS from a downward-facing ADCP, and RCBS from upward-facing ADCP observed at the study site, 17.0-18.6 November 1999. Note that color-axes differ among plots.

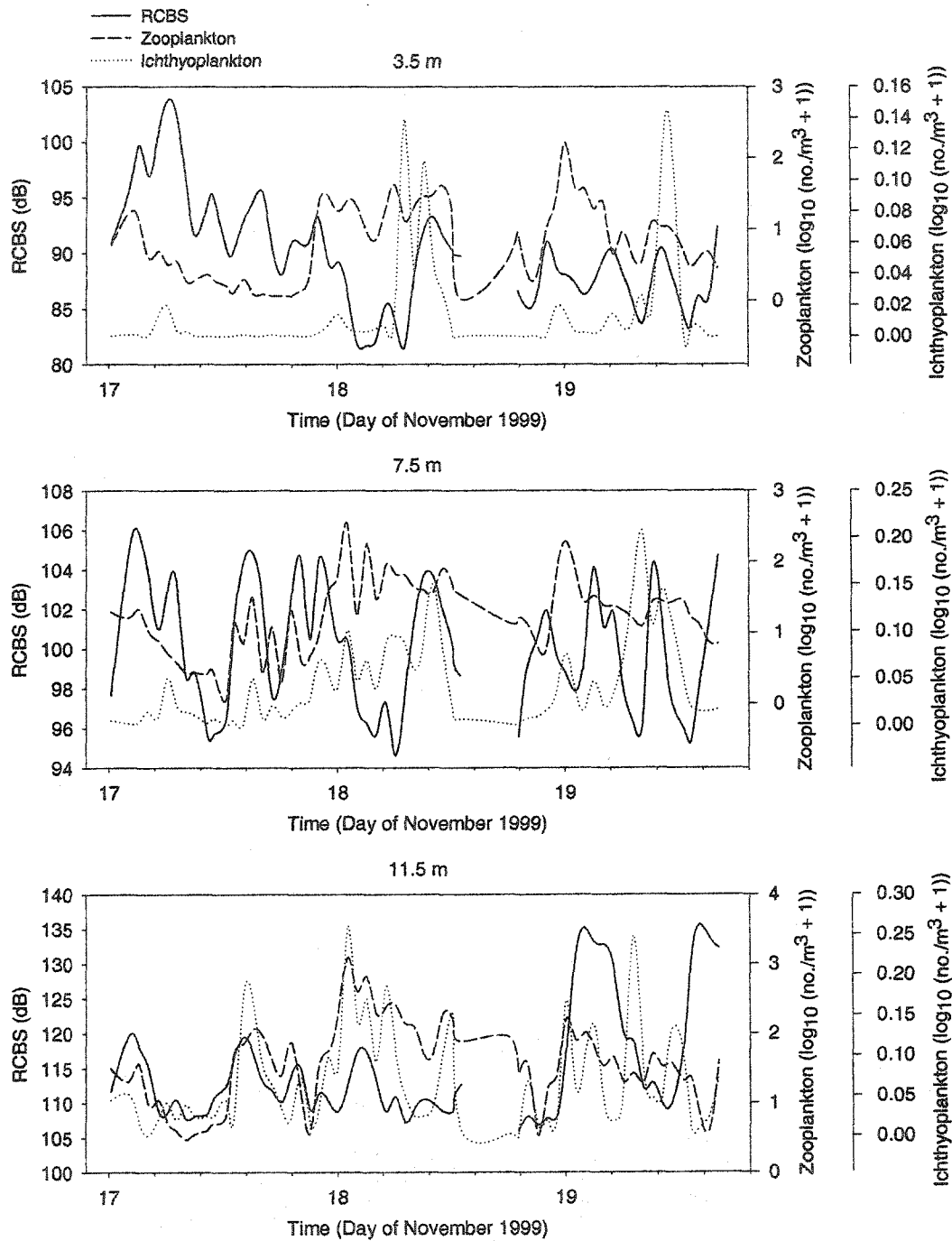


Fig. 11. RCBS, log transform zooplankton concentration, and log transform ichthyoplankton concentration at 3.5, 7.5, and 11.5 m observed at the study site, 17-19 November 1999. Note that y-axes differ among plots.

appears to be a strong surface reflection in the upward-facing ADCP signal (side lobe effects). A comparison of RCBS between the downward and upward-facing ADCP for individual 0.5-m depth bins, 1.5-11.5 m deep, produced correlation coefficients of 0.59-0.90.

Comparisons of RCBS, total zooplankton concentration, and total ichthyoplankton concentration at each depth fished by the channel nets revealed little relation among the factors (Fig. 11). Correlation coefficients between log transformed zooplankton concentration and RCBS were -0.26, -0.07, and 0.04 for 3.5, 7.5, and 11.5 m respectively. Similarly, correlation coefficients between log transformed ichthyoplankton concentration and RCBS were -0.12 at 3.5 m, -0.09 at 7.5 m, and 0.07 at 11.5 m. Single-factor linear or power regressions using zooplankton concentration, ichthyoplankton concentration, and total estimated zooplankton volumes versus RCBS produced r^2 -values of 0.14-0.22 (TABLE 2). Similarly, multiple-linear regressions using combinations of log transformed zooplankton and ichthyoplankton concentrations versus RCBS produced r^2 -values of 0.21-0.31.

TABLE 2. Results of regressions between log transformed zooplankton and ichthyoplankton concentrations versus RCBS observed at the study site 17-19 November 1999.

Independent Variables	Regression Type	r^2	n
Total zooplankton (Fig. 10)	linear	0.18	148
Total estimated volume zooplankton ($\text{mm}^3 \text{m}^{-3}$)	linear	0.15	148
Total zooplankton	power	0.17	148
Total ichthyoplankton (Fig. 10)	linear	0.14	177
Total ichthyoplankton	power	0.22	177
Total zooplankton, total ichthyoplankton	multi-linear	0.21	148
Eight most abundant zooplankton taxa (TABLE 1)	multi-linear	0.31	148
Ichthyoplankton (stages): Atlantic menhaden (3), Atlantic croaker (3), Summer flounder (4)	multi-linear	0.31	177

Plots of RCBS showed similar patterns to time series of reciprocal light transmission and fluorescence, most notably between day 17.0-17.6 and day 19.0-19.5 November 1999 (Fig. 12), with correlation coefficients for individual 0.5-m depth bins ranging from 0.40-0.65 between 1.5-11.0 m depth. Similarly, fluorescence and RCBS had correlation coefficients of 0.21-0.66 for the depth range 1.0-11.0 m. Plots of reciprocal light transmission and fluorescence were very similar over the entire sampling period.

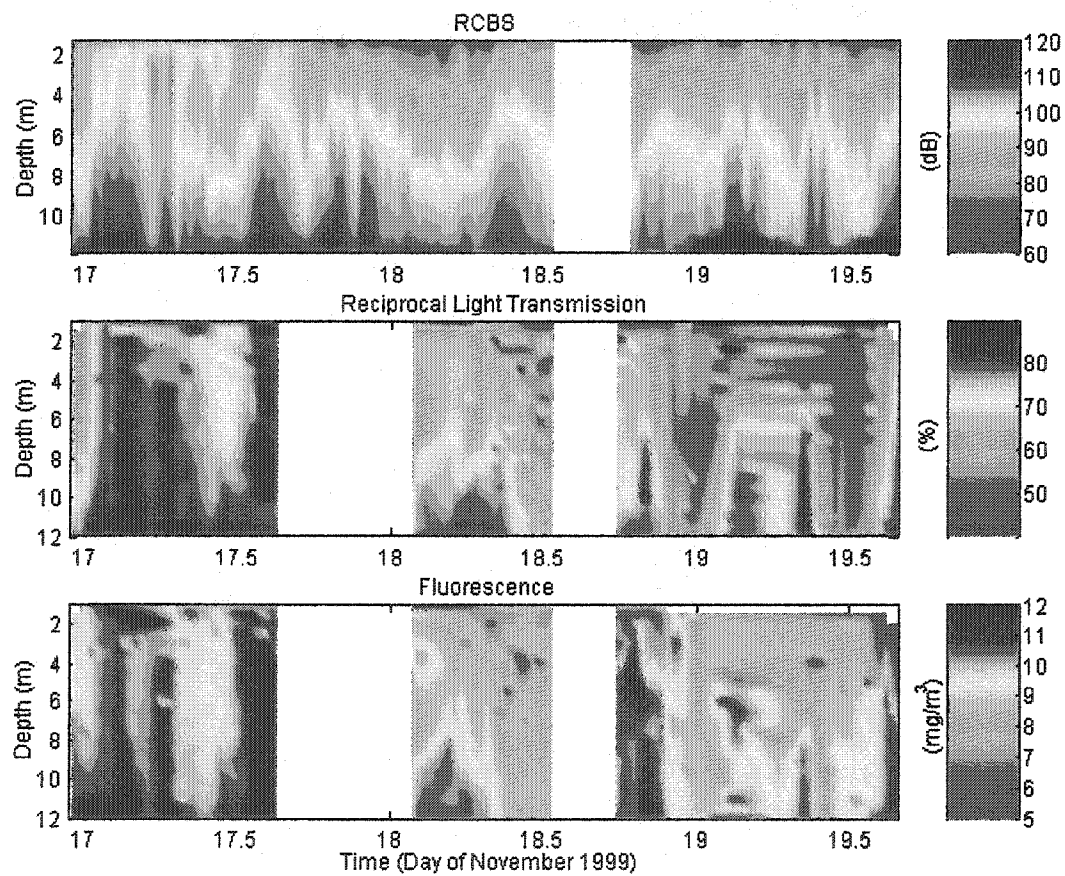


Fig. 12. Range corrected backscatter, reciprocal light transmission, and fluorescence at the study site, 17-19 November 1999.

Finally, east-west flow and RCBS at 11.0-12.0 m were compared using auto-correlation and cross-correlation analyses for time periods (days 17.0-18.5 and 18.8-19.7 November 1999) encompassing 37 and 22-hr of observations respectively. The autocorrelation function from the RCBS time series revealed a conspicuous 12 hr periodicity (Fig. 13). Cross-correlation coefficients between east-west flow in bottom layers and RCBS at similar depths were as high as 0.7 and 0.9 for day 17.0-18.5 and 18.8-19.7 respectively, with no indication of a phase lag between the two series (Fig. 13).

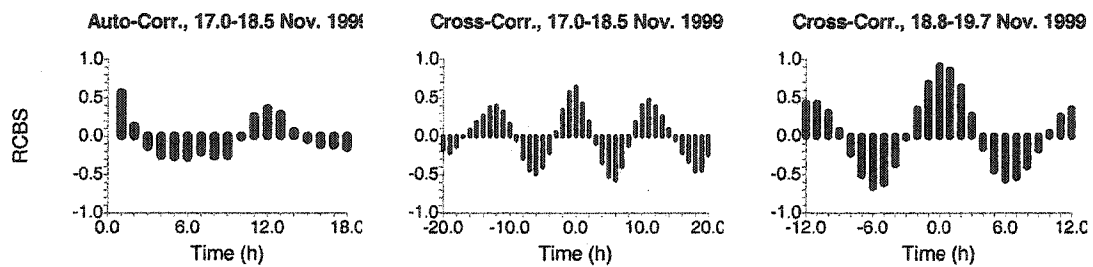


Fig. 13. Auto-correlation of RCBS for days 17.0-18.5 November 1999 (left) and cross-correlation of RCBS versus east-west (tidal) flow for days 17.0-18.5 (center) and 18.8-19.7 (right) November 1999.

DISCUSSION

Strong northwest winds present at the beginning of the study strongly influenced tidal and density driven currents, and generated significant variability in the physical properties of the water column over the North Channel of the Chesapeake Bay. The result was not surprising given that Valle-Levinson et al. (2001) showed that northwest wind $>12 \text{ m s}^{-1}$ will cause efficient flushing of Chesapeake Bay. In our study area a 10-15 m s^{-1} northwest wind opposed the flood tide and generated weak flood flows, especially near the surface. Time-averaged, depth-integrated flow was out of the estuary during the period, and two distinct water masses passed through the study area: relatively warm-fresh (12.5-13.2°C and 24.7-30.0 psu) Chesapeake Bay water, followed by a cool-fresh (11.2-12.5°C and 24.7-30 psu) water-mass that probably originated from farther up-Bay.

As the northwest wind weakened, coastal waters (30.0-32.5 psu) rebounded into the study area, as evidenced by a weak ebb tide between two strong flood tides immediately following the wind shift (day 17.7-18.4). After this net volume inflow, the interaction of a semidiurnal tide and density driven currents generated a classical estuarine circulation for the remainder of the sampling period, with overall residual currents moving into the estuary near the bottom and out of the estuary at the surface. The bimodal temperature distribution evident in the coastal water-mass was the result of the water from inside Chesapeake Bay, forced out on the ebb tide, being approximately 1.0°C cooler than the water-mass brought into the bay by the flood tide flows.

We attributed most of the variability in zooplankton abundance and diversity anomalous tidal currents caused by variability in the local wind field. Although all major taxa were observed in the fresh water-masses, low abundance of zooplankton in these water-masses indicates low abundance in Chesapeake Bay waters during the study. Only *M. bigelowi*, crab megalopae, and crab zoeae were caught in any appreciable numbers during the period of strong northwest winds, suggesting that these taxa present in the upper reaches of Chesapeake Bay. Zooplankton abundance peaked after the weakening of the northwest wind and during the incursion of salty coastal water. Four of the six dominant zooplankton taxa were most abundant in the returning salt water-masses and

numbers peaked during periods of maximum flow. The largest peak of crab zoeae came near the end of the study during a daytime, ebb tide (centered on day 19.6) that differed from other ebb tides of the study in that the wind was blowing from the southeast. Wind stress presumably pushed surface water from the adjacent shoals and main channel towards the study site.

The overall abundance of three dominant taxa and the vertical distribution of another showed diurnal variability. Several species (*M. bigelowi*, *L. faxoni*, and *L. aestiva*) were collected in higher concentrations during the night at all depths than during the day, suggesting that these animals may be using vision to avoid nets during the day (Orr 1981, Zhou et al. 1994). However, we found *M. bigelowi* and *L. aestiva* at highest concentrations near the bottom, so was possible that these animals were on or very near the bottom during daylight hours, and therefore below the range of the 11.5 m net. Crab megalopae were the only dominant taxa that showed clear evidence of diel vertical migration, with significantly more animals near the surface at night and near the bottom during the day, possibly indicating vertical excursions to find food, yet avoid their predators.

In turn, tidal stage had a significant impact on four of the six dominant zooplankton taxa and absolute tidal flow magnitude was significantly correlated with concentrations of five of the six dominant taxa during either the first or second parts of the study. Although *M. bigelowi* did not show any preference for tidal stage, abundances were significantly correlated with east-west flow at a time-lag of 0 hrs. These mysids are very common in Chesapeake Bay (Gosner 1971) and their pattern of abundance was consistent with the hypothesis of resuspension from near the bottom during peak tidal flows. More *L. faxoni*, *Sagitta* sp., and crab megalopae species were found near the surface on flood tides rather than ebb, indicating that these animals are in some way responding to flood tides and moving into the estuary near the surface, similar to what is predicted by STST (Forward et al., 1999). Alternatively, these animals may have been more abundant on flood tides simply due to a larger supply outside the bay's mouth compared to within Chesapeake Bay.

Crab megalopae and *Sagitta* sp. showed strong correlations with semidiurnal tidal flow near the bottom during 17.0-18.5 November 1999, although peak densities were

approx. 3-hr out of phase with maximum flow. This may suggest pools of these zooplankton are located within a tidal excursion, but several kilometers away from the sampling site, and do not pass through the study site until several hours after peak flow. Mean flood flows being 81% greater than ebb flows in the bottom layer could account for greater resuspension and therefore more animals high in the water column during the flood tide. It is not clear why crab megalopae and *Sagitta* sp. demonstrated weaker correlations during day 18.8-19.7, although this could be due to these taxa becoming more mixed in the bay mouth area after initial invasion from offshore. Crab zoeae were found in their highest concentrations near the surface on ebb tides, probably due to the buoyancy of the crab zoeae and a larger supply of animals inside the Chesapeake Bay than in the coastal ocean (Johnson and Hester 1989). Crab zoeae, *L. aestiva*, and *L. faxoni* had poor correlations with east-west flow during day 17.0-18.5, but improved, especially for crab zoeae and *L. aestiva*, during day 18.8-19.7. This contrast with other dominant taxa could be due to the strong northwest wind during the beginning of this study having more effect on the smallest organisms found during this study, crab zoeae and *L. aestiva*. The preferred depth of crab zoeae and *L. faxoni* were closer to the surface than the other dominant taxa, which meant the wind could have had more influence over their horizontal movements, thus producing a pattern of abundance less related to tidal flow.

Backscatter measurements between two similar ADCPs approx. 100 m apart within the North Channel agreed reasonably well. The sources of backscatter were, therefore, consistent along the channel and the measurement of scattering was relatively precise between the upward- and downward-facing instruments. However, we noted significant scattering from both the surface (for the upward-facing instrument) and the bottom (for the downward-facing instrument). The scattering was problematic because it obviously restricted our ability to draw any conclusions from ADCP measurements in near-surface and near-bottom waters.

Backscatter measurements recorded at the Chesapeake Bay mouth during the period 17-19 November 1999 proved to have low correlation with zooplankton and ichthyoplankton abundances. Indeed, r^2 -values for all depths revealed that backscatter was a poor predictor of zooplankton abundance, zooplankton volume, or ichthyoplankton

abundance. Acoustic backscatter has been most closely correlated with total scattering volume in past studies (Stanton et al. 1994a), although in our study the regression of zooplankton volume to RCBS actually made the fit slightly worse than one based on zooplankton abundance. It remains possible that the discrepancy was due to imprecise estimation of organism volumes or the storage of zooplankton specimens in ethanol for over a year before processing. However, we suspect that it is more likely that measurements of RCBS in the Chesapeake Bay mouth were uncorrelated with zooplankton abundance, and therefore, uncorrelated with any derived measurement of biomass.

Backscatter is probably caused by a number of different types of particles, including zooplankton, ichthyoplankton, phytoplankton, and suspended sediment. Measurements of light transmission and fluorescence were better predictors of RCBS than were zooplankton or ichthyoplankton abundances, based on depth specific correlations and visual inspection of color plots. Sediment or phytoplankton in high densities, as is often present in turbulent estuaries, could cause high backscatter values (Wiebe et al. 1997). Time series analysis showed significant correlations between tidal current magnitude and RCBS near the bottom with no phase lag. This is further evidence that backscatter in the study area was mainly caused by passive particles, such as sediment, being resuspended off the bottom.

CONCLUSION

Our study indicated that the greatest variability in zooplankton abundance was due to transport of animals from the coastal ocean due to the northwest wind. Strong northwest winds pushed Chesapeake Bay water out of the Bay mouth. With the relaxation of the wind, coastal water responded and produced a period of strong flood flows into Chesapeake Bay, carrying a number of zooplankton taxa with it. Light southerly winds between episodes of stronger northerly winds could further distribute plankton through Chesapeake Bay and its tributaries. The weather pattern described is typical for the southern Chesapeake Bay in late fall and early winter (Valle-Levinson et al., 2001).

Diel factors caused the highest variability in overall abundance of zooplankton within water-masses but appeared to play little role in the expected vertical distribution. Crab megalopae were the only zooplankton taxa that clearly demonstrated nightly excursions to the surface. Variability in overall zooplankton abundance due to day-night contrasts was probably a result of net avoidance during the day. It was possible, however, that layers of organisms were compacted into the two meters of water between the deepest net and the bottom during the light periods.

Although our sampling scheme offered a high-resolution view of depth-dependent zooplankton abundance, it offered no means to distinguish between STST and passive resuspension. All the dominant taxa except *L. faxoni* exhibited abundance patterns that were correlated with tidal flow during at least part of the study, suggesting that resuspension is probably an important determinant of horizontal movements. Specifically, crab megalopae and *Sagitta* sp. exhibited depth-dependent abundance patterns that could most easily be explained through passive resuspension from near the bottom during swifter flood flows. Larger or more concentrated pools of zooplankton in the coastal ocean than in the Chesapeake Bay mouth could also contribute to higher abundances on flood tides. Indeed, it would be difficult to design a study that could discern between active behavior and passive transport in zooplankton. It is likely the overall movement of zooplankton is some combination of the organism reacting to

environmental cues and being transported by the currents, which probably varies between species, sub-species, and life stages.

We were unable to derive meaningful biological data from ADCP backscatter at the sampling location. When a single frequency is used, as with the ADCP, it is impossible to resolve the size or type of the particles that caused the backscatter (Greenlaw, 1979; Medwin and Clay, 1989). In order to use a single frequency echo sounder such as the ADCP in this setting, a great deal of on-site calibration must be done, requiring a significant number of physical samples to try to independently quantify the scatterers present in the water. Sampling on time scales closer to the temporal resolution of the ADCP would also help to identify the potential dominant scatterers, allowing more accurate and detailed calibration curves to be fit. This may be more work than simply collecting the samples in traditional ways (pumps and nets).

On the other hand, ADCP RCBS could be used as a depth-resolved measure of total suspended particles in the water column. This potential was demonstrated by the good correlation between the two independent ADCPs showing that the sources of scattering were consistent and that the measurements were reasonably precise. Wiebe et al. (1997) used a 420 kHz echo sounder to study zooplankton on Georges Bank and reported sand suspended in the water, which sometimes dominated the backscatter signal. Indeed, suspended sediments are probably even more prevalent in a relatively shallow estuary such as Chesapeake Bay. The RCBS could be calibrated using a laboratory setting, controlling the amount of suspended sediment in a water tank to establish a calibration curve with the ADCP. The result would be data similar to that collected by a light transmissometer on some CTDs, but with better temporal and/or spatial resolution.

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Professional Experience

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Minority Serving Institution Cruise. May 2001. Multi-institution effort to study Hudson Canyon's associated physics and biology. Sponsored by NOAA aboard Albatross IV.

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