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USING ECHO INTENSITY TO CORRECT MOORED ADCP DATA FOR FISH-BIAS ERRORS AT 0°, 170°W

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ABSTRACT. Acoustic Doppler current profilers (ADCPs) have been deployed on both subsurface and taut-line surface moorings to measure upper ocean currents in the equatorial Pacific. The moored ADCP velocity measurements are included as part of the data base from the Tropical Atmosphere Ocean (TAO) array, which provides measurements of upper ocean and atmospheric variability in support of climate studies. Surface moorings tend to attract pelagic fish, which sometimes school around the mooring and bias the ADCP velocity measurements. Therefore the fish-bias velocity errors, which have been as large as 80 cm s^{-1} in the surface moored ADCP data, must be eliminated as much as possible from the ADCP velocity time series. In situ mechanical current meter (MCM) data have been used to correct the fish-bias velocity errors in the surface moored ADCP data at 0°, 110°W and 0°, 140°W. The equatorial ADCP mooring at 170°W has been deployed as a subsurface mooring since 1988, except for a 1-year deployment as a surface mooring beginning in March 1993. No MCM velocity data are available to correct these surface-moored ADCP velocities for fish-bias errors. In this study, a procedure is developed to reject fish-biased velocity data in postprocessing based on the ADCP echo-intensity measurement. This method significantly improves the accuracy of the velocity data, but at times so much of the hourly data is rejected that a daily averaged velocity could not be computed.

1. Introduction

As part of the Tropical Ocean-Global Atmosphere (TOGA) program, an array of moorings was established in the tropical Pacific to measure upper ocean velocity, temperature, and surface winds. These measurements provide long time series on upper ocean and atmospheric variability for analysis of short-term climate variations, particularly those relating to the large-scale interaction of the atmosphere and ocean. Presently, approximately 70 wind and thermistor chain moorings are included in the Tropical Atmosphere Ocean (TAO) array, providing data from the tropical Pacific in near real time via satellite (Hayes *et al.*, 1991; McPhaden, 1993, 1995). Near-surface currents are measured at five locations on the equator, either by ADCPs (acoustic Doppler current profilers) or MCMs (mechanical current meters).

In May 1988 a subsurface RD Instruments' ADCP, for measuring upper ocean currents, was deployed in the vicinity of an ATLAS mooring measuring temperature and winds at 0°, 170°W. This subsurface mooring was maintained until March 1993. At this time a PROTEUS mooring (McPhaden *et al.*, 1991) was deployed to facilitate real-time transmission of the velocity data via satellite. PROTEUS consists of an ADCP mounted in a downward-looking position on a taut-line surface mooring. Unfortunately, significant errors were apparent in the velocity data due to acoustic reflections from fish which school around surface moorings. In March 1994, the surface mooring was recovered and a subsurface mooring deployed in its place. Although a school of fish may, on

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occasion, swim though the acoustic beam of a subsurface mooring, these moorings do not attract fish and the ADCP data from subsurface moorings are essentially free of fish-bias errors.

Freitag *et al.* (1992) and Plimpton *et al.* (1995, 1997) also found fish-bias errors in ADCP velocities from equatorial PROTEUS moorings at 110°W and 140°W. Since these data were collected concurrent with MCM velocity measurements at six or seven depths, extensive analysis of the fish-biased measurements was possible. As a result, RD Instruments created a fish-rejection algorithm in an attempt to detect and reject fish-biased data on an individual ping basis before ensemble averaging. However, large fish-bias errors remained even after installation of the algorithm in March 1992. Thus, the TAO project phased out PROTEUS moorings, and since March 1995 all ADCPs in the TAO array have been deployed on subsurface moorings.

Significant fish-bias errors most likely occur in the data from the 0°, 170°W PROTEUS mooring. However, no in situ velocity data are available for the detection or correction of errors in these velocities. Evaluation of the ADCP measurements of percent good and echo intensity indicates the presence of fish in the 170°W data. Thus, a procedure is presented in this report to reject fish-biased velocity data in postprocessing using only data collected by the ADCP.

2. Fish Bias

Downward-looking, 153.6 kHz, RD Instruments ADCPs were deployed on equatorial surface moorings with the acoustic beams angled 30° from vertical. Data were collected with 8-m bin and pulse lengths, at a 1-second sample rate for 6 minutes once per hour. The ADCP transmits an acoustic signal, determines time-gated Doppler shifts along each of the four beams, and then computes beam-direction velocities as a function of range. The beam velocities are converted to Earth coordinates using beam geometry and direction from a KVH flux gate compass. The frequency shift in the return signal is caused by the relative motion of oceanic scatterers with respect to the ADCP transducers. For measurement of ocean currents, it is assumed that the movement of the scatterers is due, on the average, to oceanic advection.

In the absence of fish, the most significant ADCP velocity errors in the equatorial Pacific are due to skew errors from misposition of the ADCP tracking filter. The magnitude of the skew error depends on the strength and duration of significant horizontal velocity gradients and the ADCP setup parameters (Chereskin and Harding, 1993). Beginning in fall 1991, filter skew error has been minimized in the PROTEUS moorings by use of the 600-Hz low-pass filter bandwidth in the higher shear portions of the water column. Even for extreme conditions where the horizontal velocity shear approaches 0.1 s^{-1} for part of the water column, the filter skew error is less than 4 cm s^{-1}. For more typical equatorial velocity shears (less than .04 s^{-1}) the skew error is less than 2 cm s^{-1}. In contrast, the standard deviation due to random error for a PROTEUS ensemble average over 360 pings is 0.7 cm s^{-1}.

Pelagic fish are at times attracted to the vicinity of surface moorings. Since their mean movement is not due to advection by currents, their presence in the acoustic beam will bias the velocity measurements. For example, if the echo intensity of a fish is not much greater than that of the surrounding water, the fish will be detected in one ADCP beam but not the opposing beam. In this case, the measured horizontal velocity from the two beams would be equal to the average of the true ocean current measured in one beam and the measurement from the second beam where the ocean current velocity was biased by the fish velocity. The velocity of fish schooling around a mooring would, in the mean, be small. Thus, the signals from scatterers advected by the ocean currents would be averaged with the acoustic reflections from the fish, and the ensemble averaged measurement of non-zero horizontal velocities would be biased low. Alternately, since the scattering intensity from a fish can be much greater than the surrounding water, the same fish could be detected in the side lobes of the opposing and neighboring beams. The beam side lobes have varying relative amplitudes, with the largest side lobe down about 35 dB from the beam's main lobe. In this situation, the fish echo intensity would be larger than the scattering signal from the surrounding water in all four beams. The horizontal velocity would then tend toward zero because the fish dominant signals would tend to cancel in the computation of horizontal velocity.

In an attempt to eliminate fish-biased data during data acquisition on an individual ping basis before ensemble averaging, the RDI ADCP was equipped with a fish-rejection algorithm. This algorithm compares the echo intensity, which is an indicator of the intensity of the backscattered acoustic signal, for each of the four beams for each bin. When the echo intensity of a fish in one beam is greater than the surrounding water, then the echo intensity seen in that beam would be greater than detected in the other beams. Thus, the algorithm computes the echo intensity range (EIR) for each bin as the difference between the highest beam echo intensity and the lowest beam echo intensity. If the EIR exceeds a preset level, then the EIR is recomputed as the difference between the highest beam echo intensity and the second lowest beam echo intensity. If the recomputed EIR is also larger than the preset value, then the velocity data for the bin is set bad. The two-step process was included in order to ensure that the fish-rejection algorithm would not flag all data as bad in the event of one beam failing. The equatorial deployments used RDI command CF22 for fish rejection which rejected velocity data when the single-ping EIR was greater than 20 dB.

Freitag *et al.* (1993) and Plimpton *et al.* (1995) found that the fish-rejection algorithm was inadequate to eliminate the fish-biased velocity data from the surface-moored deployments. Many equatorial deployments at 110°W and 140°W still contained large (order 80 cm s^{-1}) fish-bias velocity errors even after the RDI algorithm rejected data with EIRs greater than 20 dB. A lower CF value would have removed more of the fish-affected data. However, Freitag *et al.* (1992) and Plimpton *et al.* (1997) have shown that too low a value for the EIR threshold will result in rejection of good data at depths below the fish-affected areas. In addition to the difficulty in setting the EIR threshold, the fish-rejection algorithm will only work if fish are detected in only one or two of the beams. Often all four beams have an elevated echo intensity because of the presence of fish as discussed above.

Since the surface moored ADCP data at 110°W and 140°W contained significant errors due to fish bias, the horizontal velocities at these sites were corrected in postprocessing using an EOF correction scheme based on in situ mechanical current meter velocity measurements (Plimpton *et al.*, 1995). The accuracy of these corrections was limited by the velocity errors in the MCM measurements, which are slightly larger than the fish-free ADCP data. One source of MCM velocity error is high frequency noise induced by mooring motion and surface waves. EG&G Model 630 Vector Measuring Current Meters (VMCMs, deployed at 10 m on TAO moorings discussed here) are relatively more effective at high frequency noise reduction than EG&G Model 610 Vector Averaging Current Meters (VACMs, used primarily at 25 m and below). Mean VACM/VMCM speed differences between instruments located at 13 m and 14 m on an equatorial taut-line mooring were 7.4 cm s^{-1}, with the VACM exceeding the VMCM mean by 12% (Halpern, 1987). At deeper depths (100 m, 120 m, 160 m) where direct surface wave influence is less energetic, mean VACM/VMCM speed differences ranged between 3.5 cm s^{-1} and 4.0 cm s^{-1}). Thus, we cannot specify the accuracy of ADCP data corrected for fish bias using algorithms based on or validated by VACM and VMCM data to better than about 5 cm s^{-1}.

3. Method for Postprocessing Rejection of Fish-Biased Data Using Echo Intensity

No MCM velocity data were available for comparison with the 170°W surface moored ADCP data. However, the failure of the fish-rejection algorithm to remove fish-biased data at 110°W and 140°W indicates that significant velocity errors probably exist in the 170°W data. Therefore, a method was developed to identify and reject fish-biased hourly ensembles in postprocessing using criteria based on the echo-intensity values.

During data acquisition, only the velocity values were rejected when the EIR values were greater than 20 dB for an individual ping. In contrast, the echo-intensity values for every ping were retained and included in the ensemble average. Thus the ensemble-averaged echo-intensity range is useful in identifying the periods when fish were present.

EIR was used for the RDI fish-rejection algorithm instead of echo intensity due to the difficulty in predicting echo-intensity values for the different temperatures and biomass concentrations found at various deployment locations. On the other hand, although the temperature and biomass would be expected to change somewhat during the duration of a deployment, after recovery a reasonable expected value for echo intensity can be determined from echo-intensity values recorded for a deployment during periods when the presence of fish was minimal. These echo-intensity averages can therefore be used to identify and reject fish-biased ensembles in postprocessing, in addition to using the ensemble averaged echo intensity range.

To evaluate the effectiveness of using echo intensity for rejecting fish-biased ensembles, a PROTEUS deployment (PR11) at 140°W from 28 April 1993 to 11 October 1993 was examined. The echo-intensity range for PR11 (Fig. 1) indicates minimal evidence of fish in the first 2 months

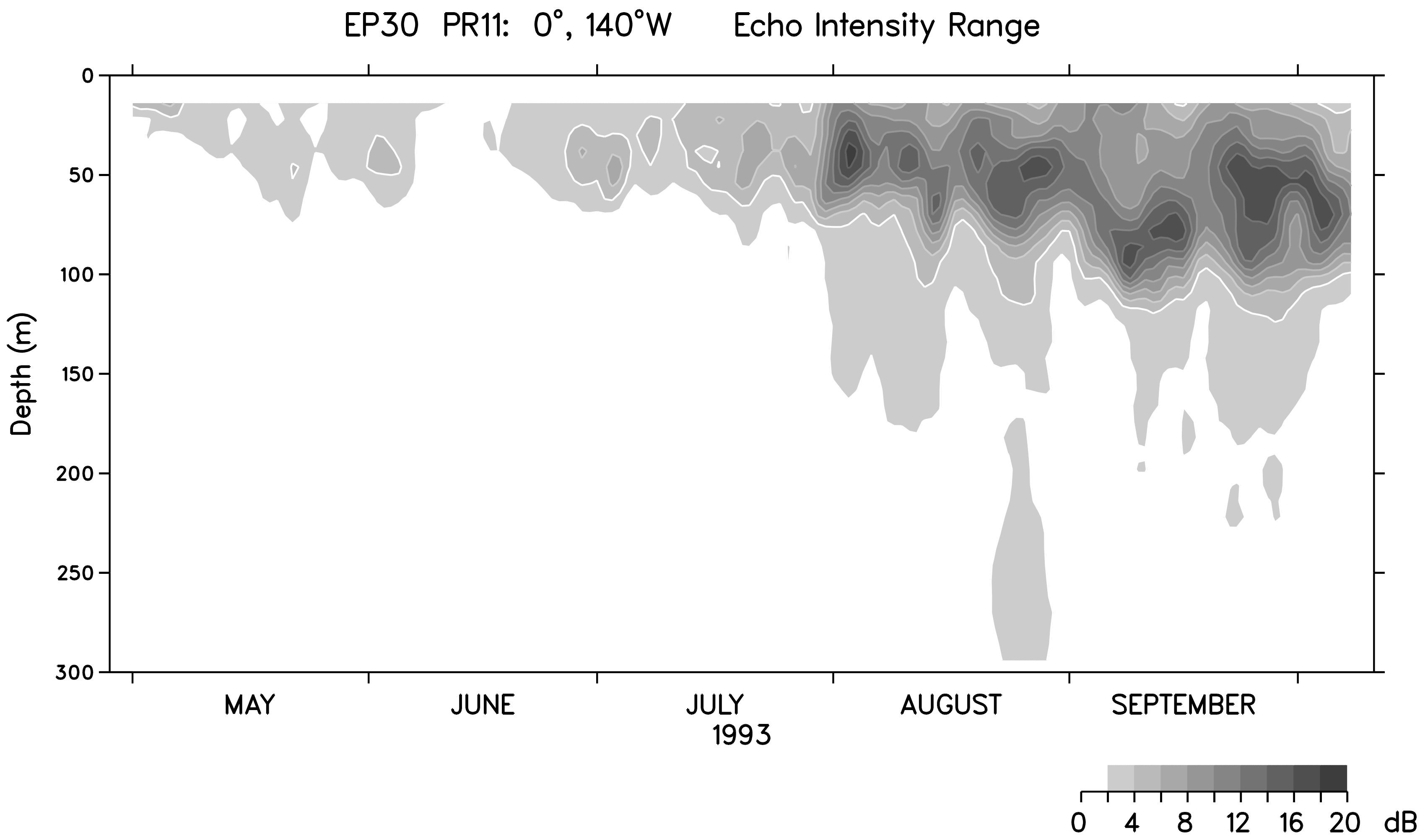

Fig. 1. ADCP echo-intensity range from 28 April to 11 October 1993 at 0°, 140°W.

of the deployment. Therefore, the data from 28 April to 28 June 1993 were used to compute mean echo-intensity values not biased by fish. A mean echo intensity was computed for each of the 24 hours in a day for each depth bin to eliminate effects of the diurnal cycle. Testing and comparison with mechanical current meters indicated that eliminating hourly data with echo-intensity values that exceed the diurnal mean echo intensity plus 4 dB substantially removed the fish-biased velocities. After this screening, individual bin data were set bad if the data both shallower and deeper were bad, or for bin 1, if bin 2 data were bad. ADCP daily averages were then computed, for which three or more hourly values were required for a good daily value.

Figure 2 shows the mean daily speeds for the mechanical current meters and the ADCP data both before and after the ADCP fish-bias screening. The upper and lower panels show the mean speeds for the first half (28 April to 19 July 1993) and the second half (20 July to 11 October 1993) of the PR11 deployment, respectively. In the first half of the deployment, where fish bias was minimal, there was little change in the ADCP speeds due to the screening. The mean speed difference after screening changed by less than 2 cm s^{-1} and there was little change in the standard deviation of the speed differences. In the second half of the deployment, ADCP minus MCM speed differences after screening were reduced by as much as 22 cm s^{-1} and the standard deviation of the speed differences did not exceed 8.5 cm s^{-1}, compared to 10–20 cm s^{-1} before screening. However, during this period, where there was considerable evidence of fish, significant loss of daily averaged data occurred with screening in the shallower depths. As many as 60 out of 84 days did not have the three good hourly values required to compute a daily average at the depths most affected by fish.

The fish-bias screening technique was also tested on PROTEUS deployment PR07 at 140°W from 1 May to 12 September 1992. From the echo intensity range (Fig. 3), there appears to be minimal presence of fish in the first third of the deployment, 1 May to 24 June 1992. The second third of the deployment, 25 June to 30 July 1992, had some periods of significant fish presence. Evidence of fish was significant for all of the last third of the deployment, 1 August to 12 September 1992. The mean diurnal echo intensity for the PR07 deployment was computed from the data in the first third of the deployment. Fish-biased velocities were then rejected if the echo intensity exceeded the mean diurnal echo intensity plus 4 dB. Means were computed from the daily speed values before and after screening and are shown in Fig. 4 for the three periods of the deployment. The first third of the deployment, which had minimal evidence of fish, shows little change after the screening. In the second third of the deployment, both the ADCP minus MCM speed differences and the standard deviation of the speed differences were reduced. During the last part of the deployment, where fish bias was most significant, the screening reduced the mean speed differences from –38, –41, and –32 cm s^{-1} to –18, –15, and –6 cm s^{-1} at 10 m, 25 m, and 45 m, respectively. Although the screening provided significant improvement, it appears that for severely biased data the screening technique may not completely reject bad data in the first two ADCP depth bins at 14 and 22 m. However, so much data were rejected in the last third of the deployment, that fewer than 13 ADCP-MCM comparisons could be made for the screened data at the shallowest three depths.

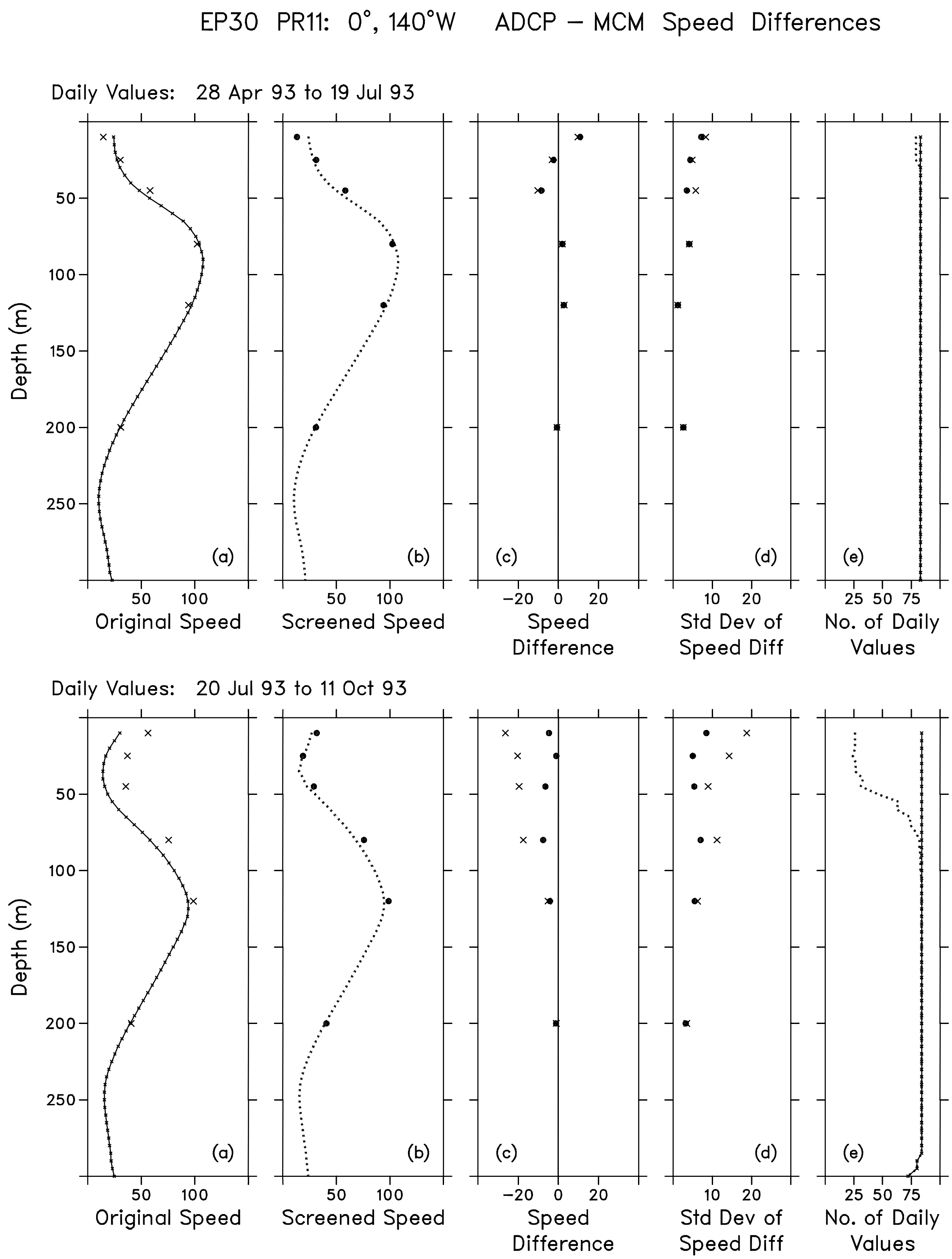

Fig. 2. Averages of daily speeds measured at 0°, 140°W by a surface moored ADCP and by MCMs from 28 April to 19 July 1993 and from 20 July to 11 October 1993. (a) Mean MCM speeds (x) and mean ADCP speeds before screening (solid line); (b) mean MCM speeds (●) and mean ADCP speeds after screening (dashed line); (c) mean ADCP minus MCM speed difference before screening (x) and mean ADCP minus MCM speed difference after screening (●); (d) standard deviation of speed differences before screening (x) and after screening (●); (e) number of ADCP daily averaged speeds (requiring at least three hourly values) before screening (solid line) and after screening (dashed line).

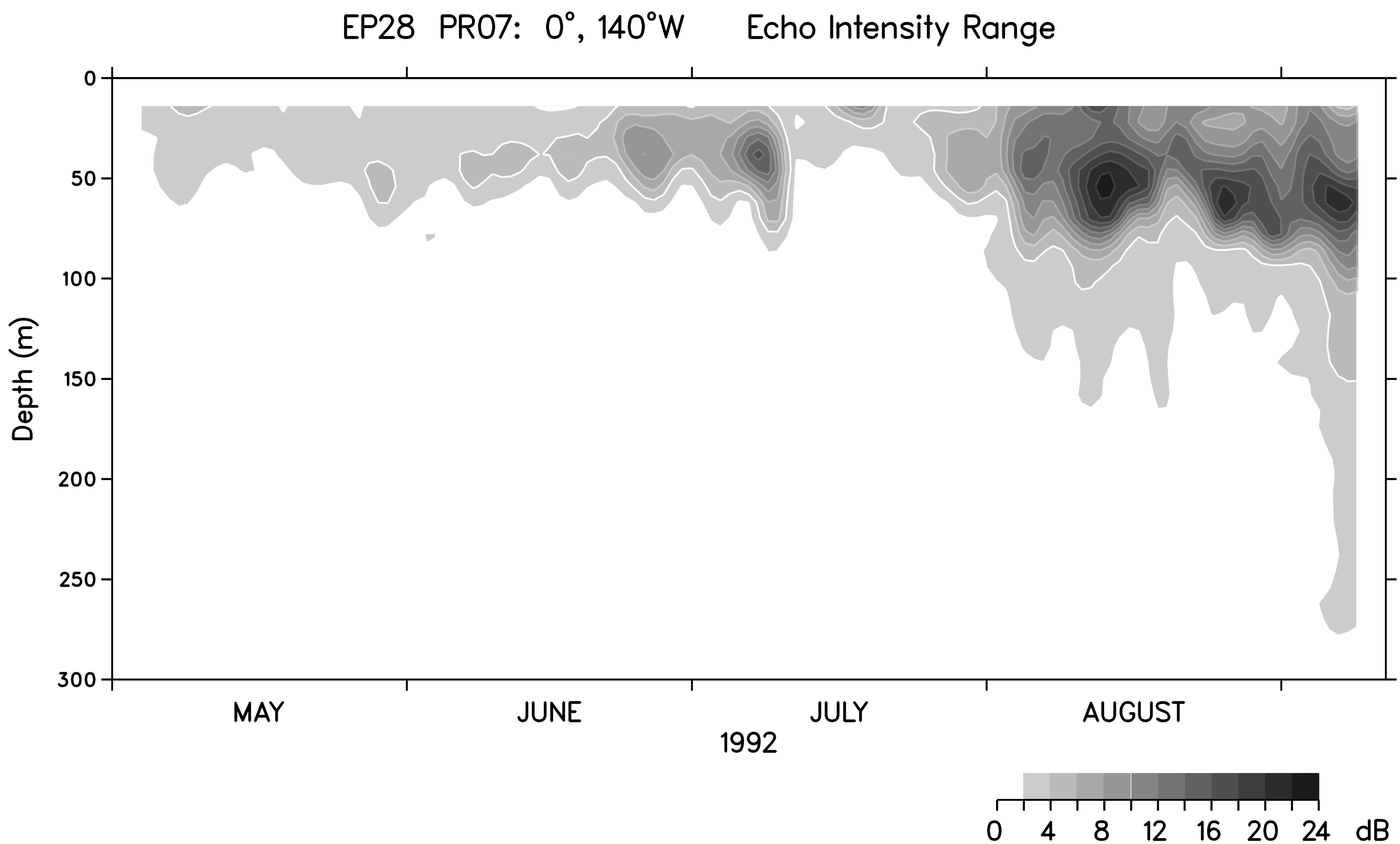

Fig. 3. ADCP echo intensity range from 1 May to 12 September 1992 at 0°, 140°W.

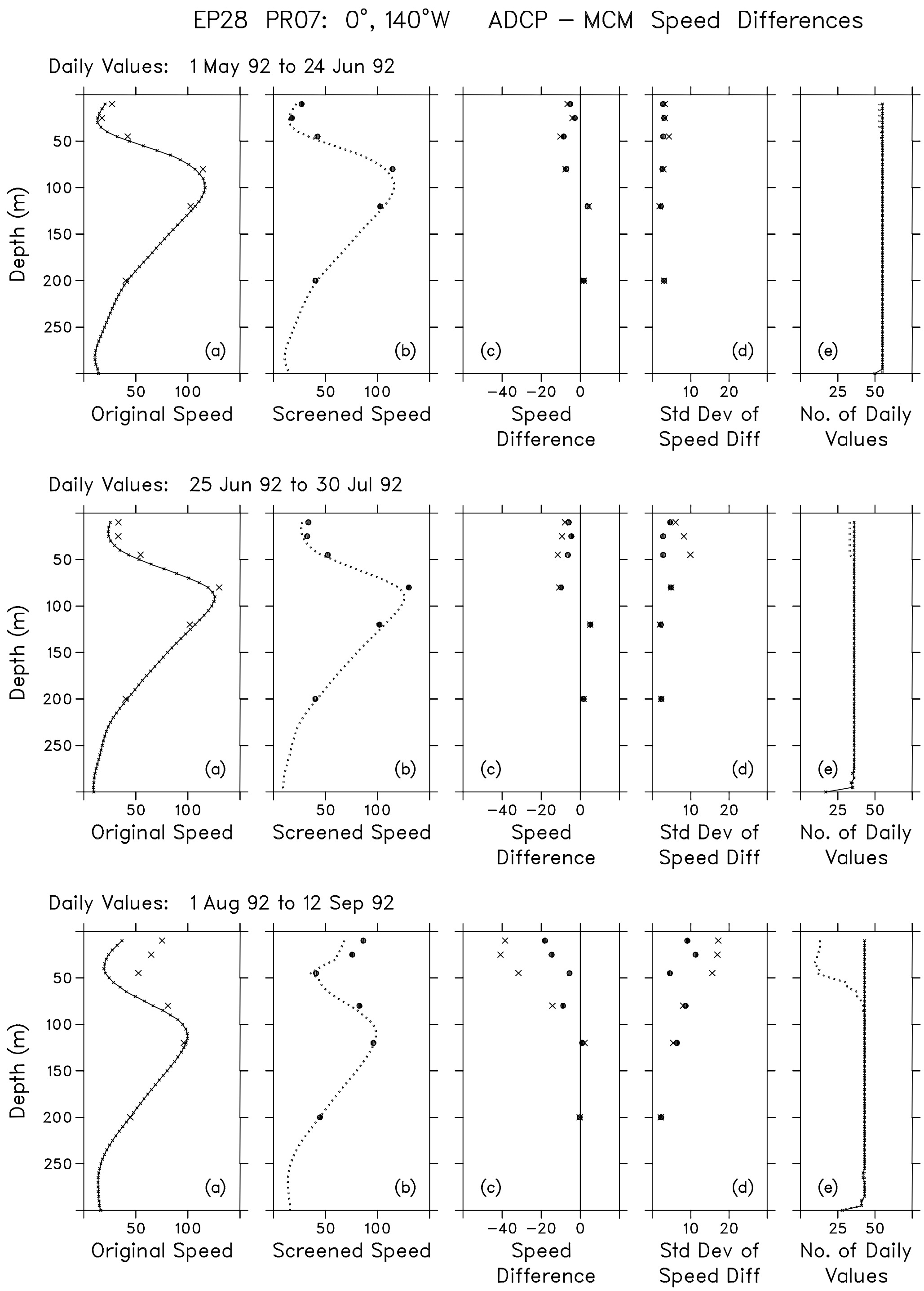

Fig. 4. Averages of daily speeds measured at 0°, 140°W by a surface moored ADCP and by MCMs from 1 May to 24 June 1992, from 25 June to 30 July 1992, and from 1 August to 12 September, 1992. (a) Mean MCM speeds (x) and mean ADCP speeds before screening (solid line); (b) mean MCM speeds (●) and mean ADCP speeds after screening (dashed line); (c) mean ADCP minus MCM speed difference before screening (x) and mean ADCP minus MCM speed difference after screening (●); (d) standard deviation of speed differences before screening (x) and after screening (●); (e) number of ADCP daily averaged speeds (requiring at least three hourly values) before screening (solid line) and after screening (dashed line).

4. Rejection of Fish-Biased Data at 170°W

The echo-intensity range at 170°W for PROTEUS deployment RTU1 from 1 April 1993 to 20 March 1994 (Fig. 5) suggests possible fish bias to depths of 150 m. However, the maximum daily averaged EIR at 170°W for the RTU1 deployment is 15 dB, compared with maximums of 25 dB and 21 dB at 140°W for PR07 and PR11, respectively. There is no direct correspondence between EIR and the magnitude of the fish bias, but the smaller EIR values at 170°W suggest that the fish bias may have been less extreme at 170°W than at 140°W. The ADCP on RTU1 was equipped with the fish-rejection algorithm set to reject velocity data during acquisition when the EIR was greater than 20 dB. In the upper 150 m (where backscattered signal strengths are high and where fish are likely to be found) data were most likely rejected by the fish-rejection algorithm (Fig. 6). The percentages of rejected pings in the second half of the deployment are large (up to 72% for a daily average and as large as 96% for an hourly ensemble) and correspond to the times of larger EIR values in Fig. 5. Below 175 m, data were eliminated due to low signal strengths. In equatorial regions, scattering target strengths tend to be lower at depth than near the surface due to the decrease in biological activity at depth. More significantly, with increased distance from the transducer, the backscattered signal strength diminishes due to beam spreading and attenuation. When the strength of the backscattered frequency signal is too low in comparison with the noise, the frequency shift (and beam velocity) cannot be determined.

Although the acquisition algorithm rejected significant percentages of fish-biased velocities (Fig. 6), it is likely that significant velocity errors remain, as was the case at 110°W and 140°W. Much of this error would likely be due to the failure of the algorithm to reject fish-biased pings when more than two beams exhibited elevated echo intensities. In order to identify the fish-biased data at 170°W that may not have been rejected by the fish-rejection algorithm, a mean diurnal echo intensity was computed for the period 1 June to 15 August 1993. From the EIR in Fig. 5, this period appeared the least affected by the presence of fish during the deployment. The ADCP data were then flagged bad if the echo intensity exceeded the mean diurnal echo intensity plus 4 dB. After this, individual bin data were set bad if the data both shallower and deeper were bad, or for bin 1, if bin 2 data were bad. ADCP daily averages were then computed, for which three or more hourly values were required for a good daily value.

Figure 7 shows the original and the screened mean daily speeds for the first half (1 April to 24 September 1993) and the second half (25 September 1993 to 20 March 1994) of the RTU1 deployment. In the first half of the deployment, where there was minimal evidence of fish, the screening resulted in very little change in the mean speeds and all daily averages were computed. In the second half of the deployment, the mean speed of the unscreened data clearly indicates the fish bias towards smaller velocities when compared with the screened speeds. As a result of the screening, as many as 74 out of 177 daily averages, requiring three hourly values, could not be computed in the upper 40 m. For the periods when a screened daily value could be computed, the largest time-averaged difference between original and screened daily speeds was at 22 m and was

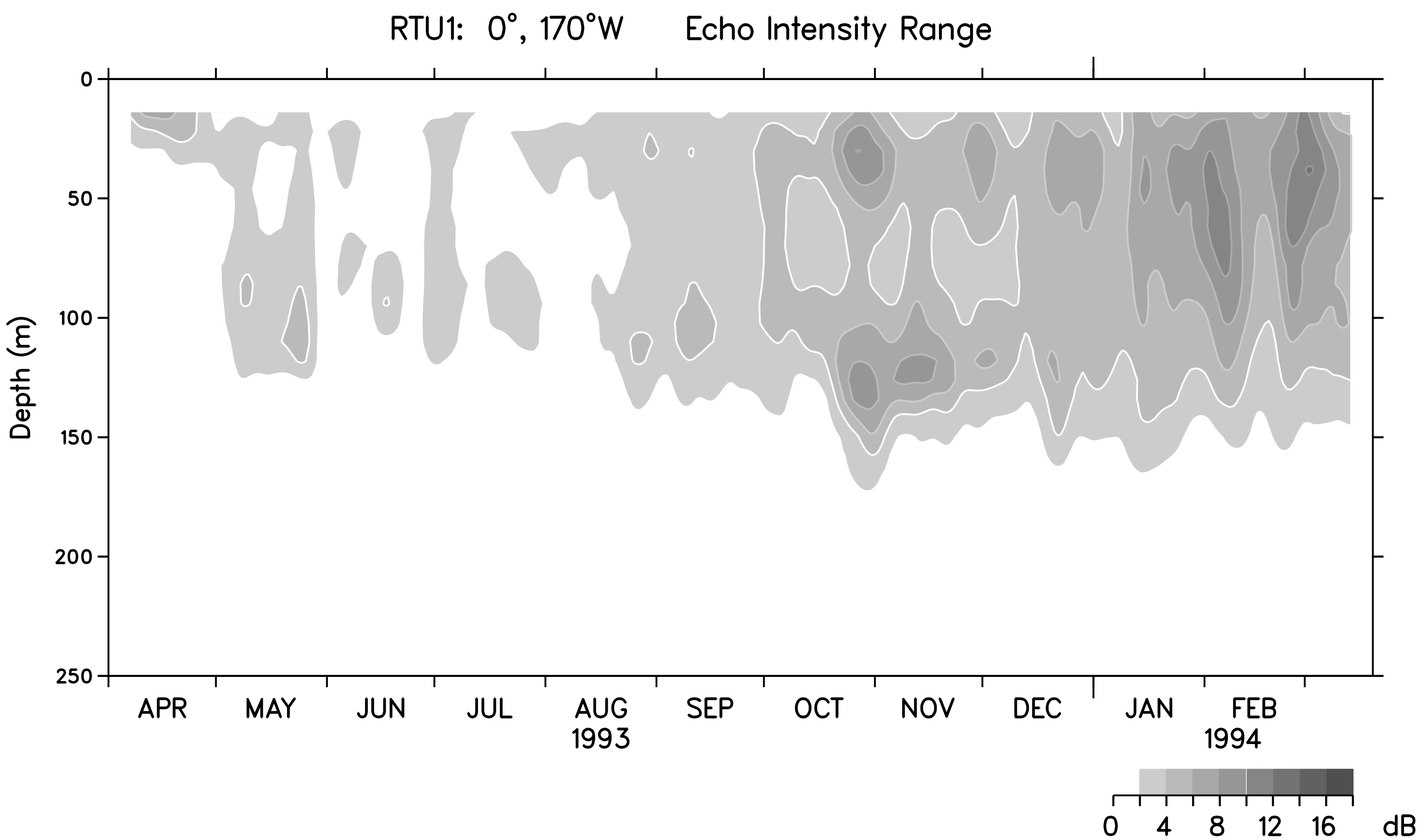

Fig. 5. ADCP echo intensity range from 1 April 1993 to 20 March 1994 at 0°, 170°W.

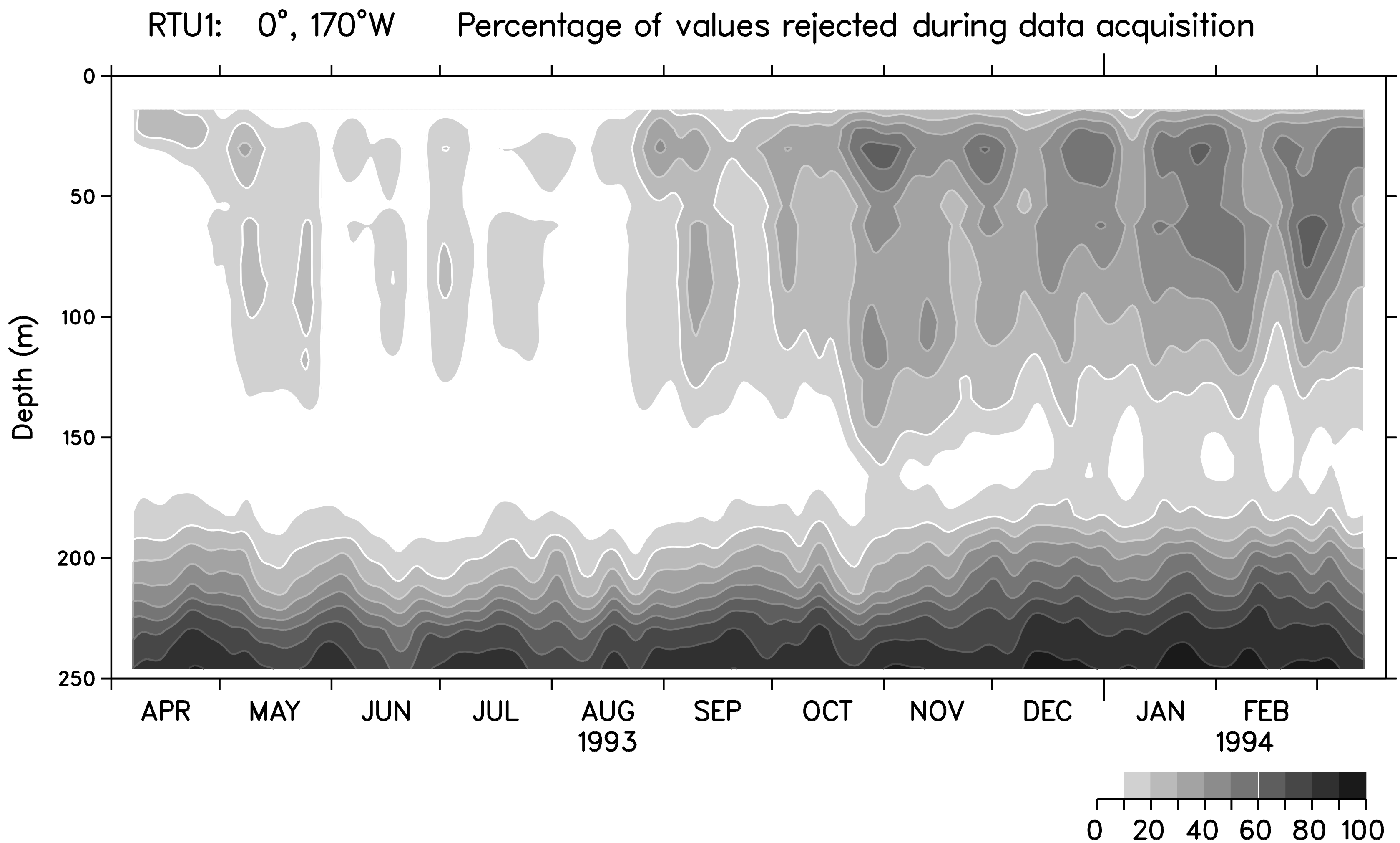

Fig. 6. Percentage of ADCP velocity values rejected during data acquisition at 0°, 170°W. Velocities below 175 m were rejected due to low signal to noise values. Shallower velocities were most likely rejected by the fish-rejection algorithm which rejected pings with EIRs greater than 20 dB.

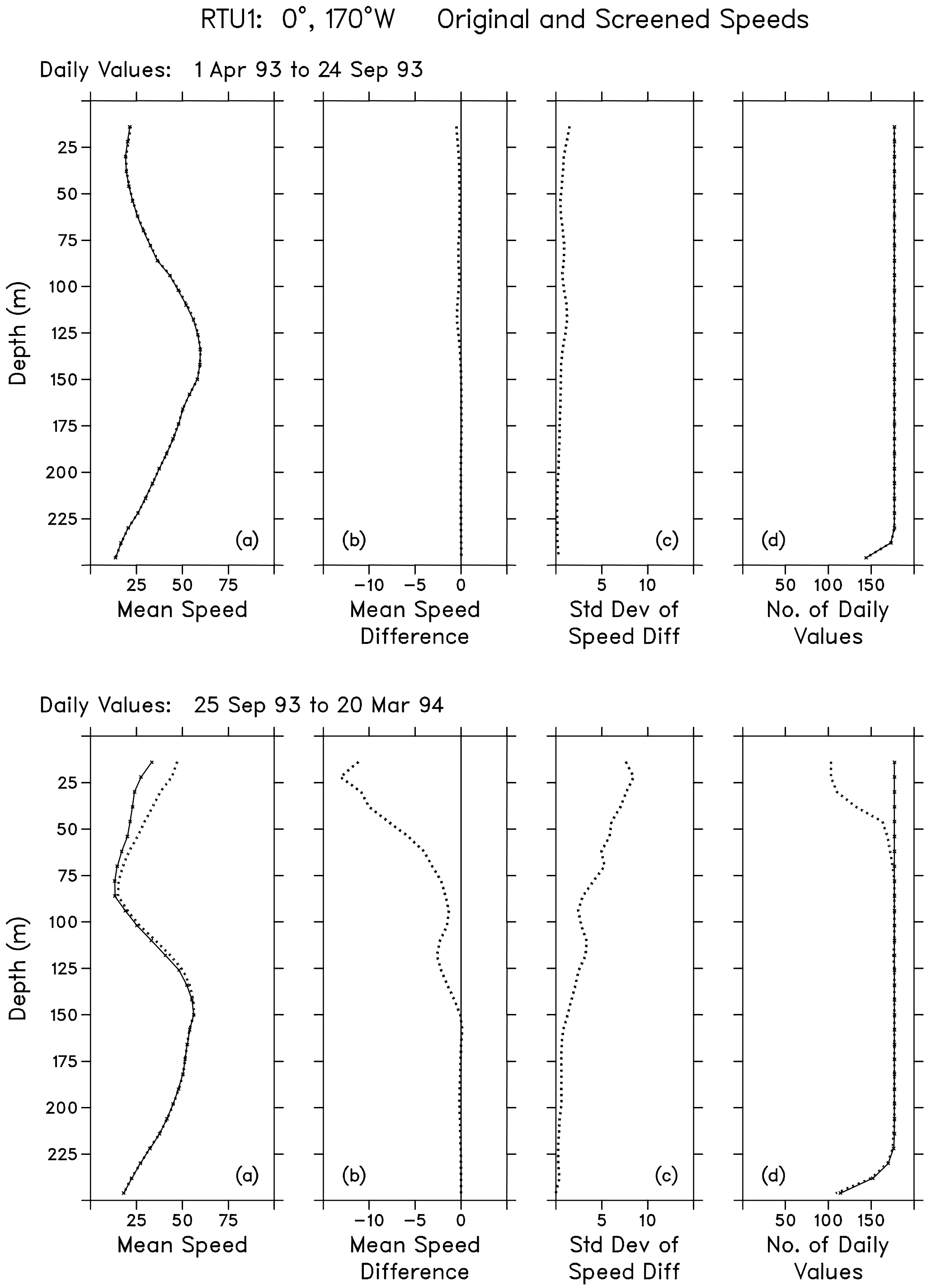

Fig. 7. Averages of ADCP daily speeds measured at 0°, 170°W from 1 April to 24 September 1993 and from 25 September 1993 to 20 March 1994. (a) Mean ADCP speeds before screening (solid line) and after screening (dashed line); (b) time averaged difference between original daily speeds and screened daily speeds; (c) standard deviation of the original minus screened daily speeds; (d) number of ADCP daily averaged speeds (requiring at least three hourly values) before screening (solid line) and after screening (dashed line).

equal to 13 cm s^{-1} for the second half of the deployment. The maximum standard deviation of the difference between the original and unscreened speeds was 8.5 cm s^{-1}, also occurring at 22 m for the second half of the deployment. In contrast, the standard deviation of the speed difference for the first half of the deployment did not exceed 1.5 cm s^{-1} for any depth.

Figure 8 shows the zonal and meridional velocities for the RTU1 deployment after postprocessing rejection of fish-biased data. The daily differences between the original and the screened zonal and meridional velocities are shown in Fig. 9. For zonal velocity, the westward currents in the upper 75 m were biased low in the unscreened data, with corrections up to 46 cm s^{-1} after rejecting the fish-biased hourly ensembles. Corrections up to 16 cm s^{-1} are evident between 100 and 150 m, the depth of the eastward flowing Equatorial Undercurrent. For meridional velocity, Fig. 9 shows northward velocity corrections up to 17 cm s^{-1} and southward velocity corrections up to 14 cm s^{-1}. Data are missing where a daily average, with at least three good hourly ensembles, could not be computed. The areas where a screened daily average could not be computed would likely have had even larger fish-bias errors if compared with the actual currents.

5. Conclusions

Velocity data from ADCPs mounted on equatorial surface moorings were biased by acoustic reflections from fish schooling around the moorings. The ADCP fish-rejection algorithm, which rejected fish-affected data based on the difference between the echo intensities of the four beams, was effective in rejecting significant percentages of biased data during data acquisition. However, large errors in the ADCP velocities still remained. The failure of the algorithm to reject all the biased data was partly due to the difficulty in setting the rejection threshold for the algorithm, but more significantly, due to the cases where the echo intensity was elevated in more than two beams. Data from mechanical current meters, set at six or seven depths, have been used in postprocessing to correct the ADCP fish-biased errors in the equatorial data at 110°W and 140°W (Plimpton *et al.*, 1995). Comparisons with the MCM velocities were also used to develop and evaluate a procedure to reject fish-biased velocities in postprocessing, when MCM data are unavailable, using only the ADCP echo-intensity data. For this procedure, a mean diurnal echo intensity for each depth bin was computed from a time period in the deployment that had only minimal evidence of fish. Hourly ensembles with significant fish bias were then identified and rejected if the echo intensity was 4 dB greater than the computed mean diurnal echo intensity. The procedure was tested on PROTEUS ADCP velocities at 140°W for two different deployments where it significantly reduced ADCP velocity errors, decreasing ADCP-MCM daily speed differences an average of 65% to 82% at depths most affected by fish bias.

The echo intensity was also used to reject fish-biased velocities in postprocessing at 170°W, where no MCM data were available. At times, however, so many of the hourly ensembles were rejected that a daily average could not be computed at some depths in the upper 75 m. For the available daily averaged data, comparison of the speeds from before and after the echo-intensity

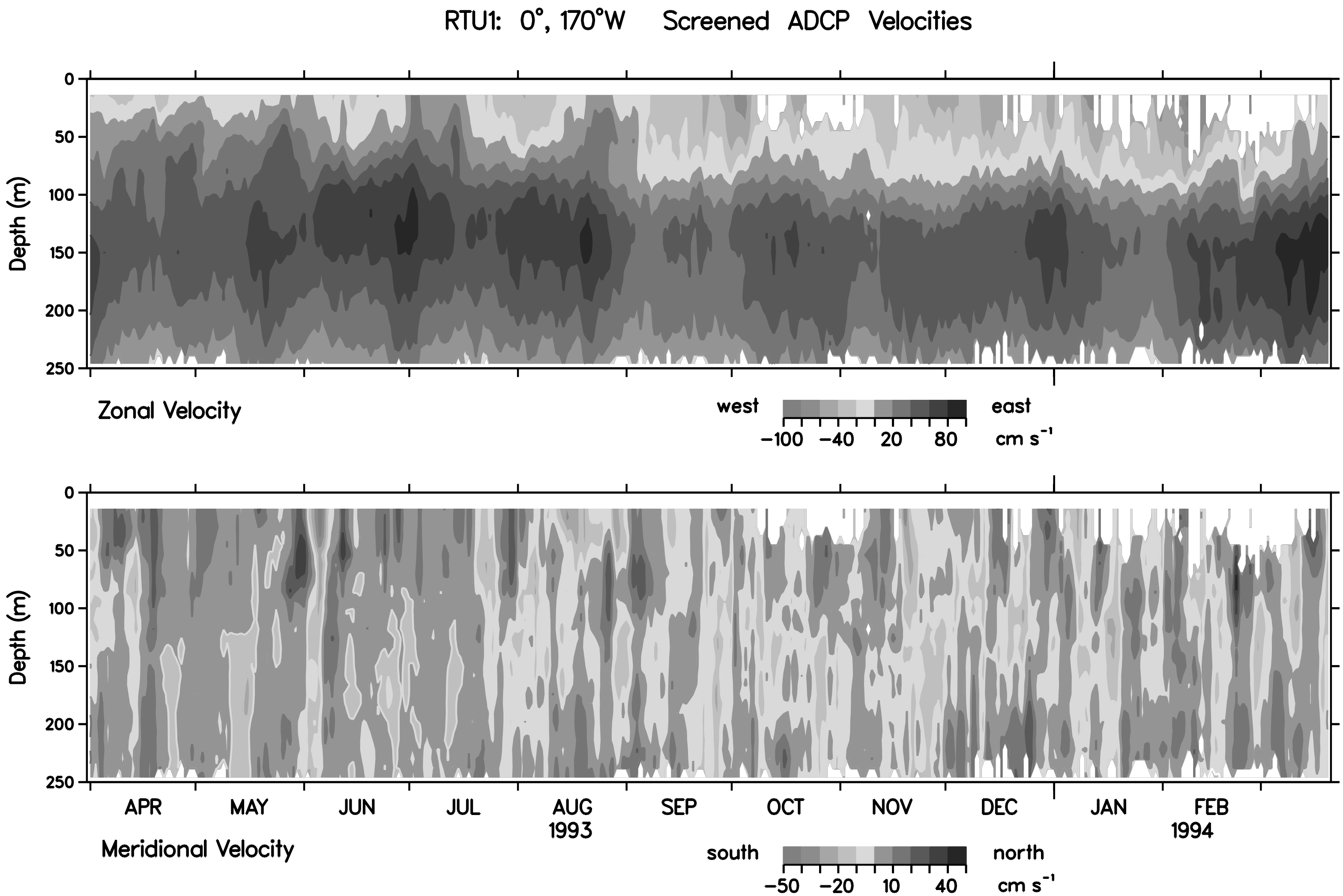

Fig. 8. Contours of zonal and meridional daily averaged velocities at 0°, 170°W after the hourly fish-biased velocities were rejected by the echo-intensity screening technique. During certain periods, less than three good hourly values remained and a daily velocity value could not be computed.

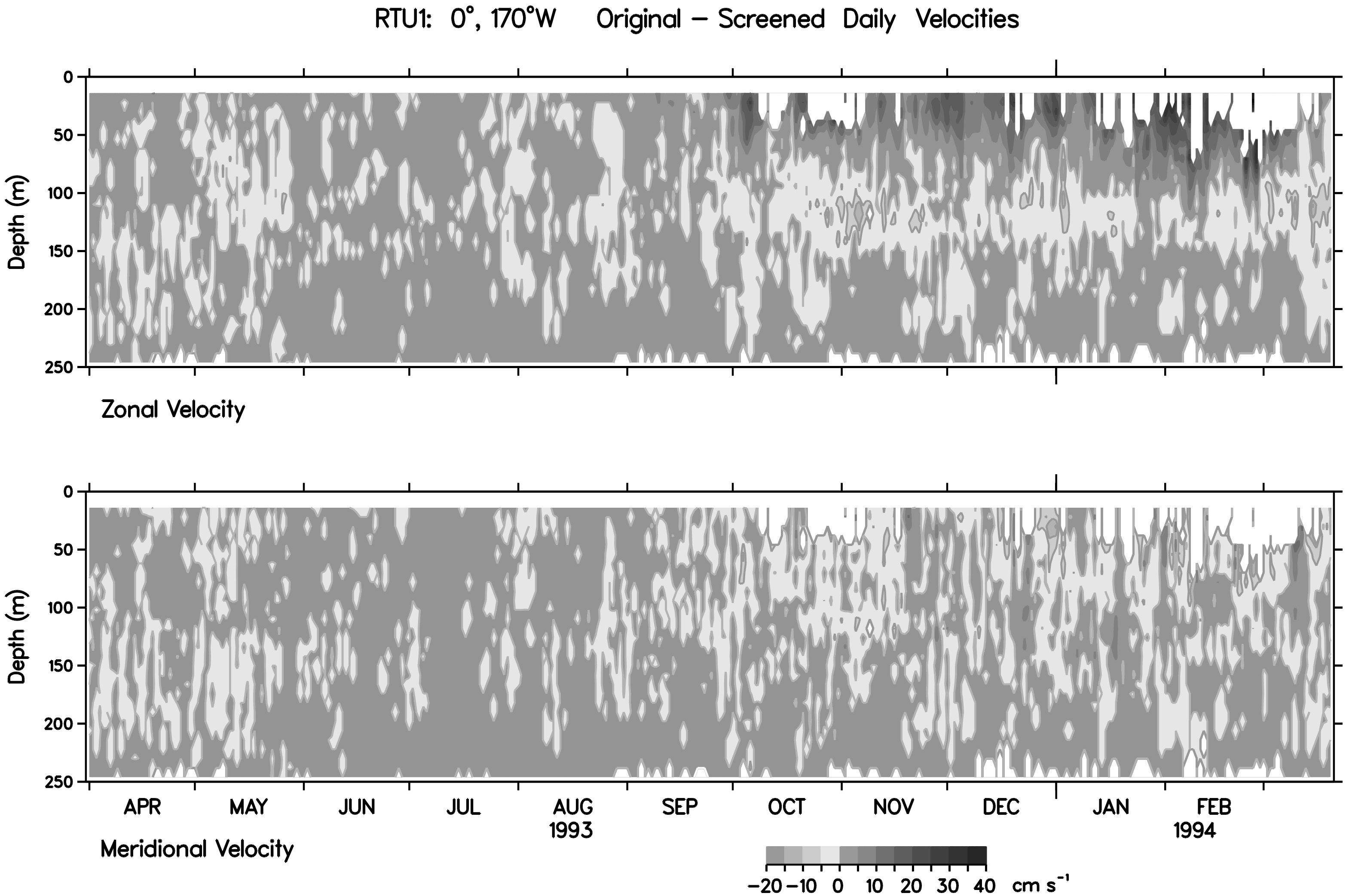

Fig. 9. Contours of the difference between the original and screened ADCP zonal and meridional velocities at 0°, 170°W. The westward flowing South Equatorial current in the upper 75 meters was biased toward zero in the original data. In the screened data the westward velocities were greater (more negative), resulting in large (up to 46 cm s^{-1}) original minus screened zonal velocity differences.

screening showed significant improvement in the ADCP velocities. For example, for the second half of the RTU1 deployment at 170°W, the time averaged screened speeds were 13 cm s^{-1} greater than the unscreened speeds at 22 m depth, indicating that fish-biased ensembles were rejected by the screening technique. The screening resulted in even larger differences at 140°W, where the screened speeds were greater than the unscreened speeds at 22 m by 22 cm s^{-1} for the second half of PR11 and by 26 cm s^{-1} for the last third of PR07. The smaller speed difference coupled with smaller echo intensity range at 170°W supports the idea, proposed by Freitag *et al.* (1993), that fish bias is greatest in the eastern Pacific, at 110°W and 140°W, and decreases to the west such that it is nearly negligible for most deployments in the western Pacific, at 156°E and 165°E. This suggests a correlation between fish bias and overall levels of biological productivity which, in the equatorial Pacific, are related to the depth of the thermocline and nutriciline.

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