OBSERVATIONS OF WAVES AND LANGMUIR CIRCULATION WITH DOPPLER SONARS

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ABSTRACT

In October-November 1983, Doppler sonars mounted on the Research Platform FLIP were used to scatter 75 kHz sound from the underside of the sea surface at low angle, as well as from the interior of the mixed layer. Surface gravity waves were easily seen in velocity estimates from the surface scattering sonar, even though the wave conditions were unusually calm. Valid measurements of sea surface motion were obtained over the range interval 600 to 1400 m from FLIP. A second sonar, which transmitted horizontally and scattered from the interior of the mixed layer, also sensed surface waves, although with amplitude reduced in proportion to the decay of the motions with depth. Wavenumber frequency spectra of the observed motions are consistent with linear theory. In addition, lower frequency motions were detected, which are consistent with Langmuir circulation. While the sonars lack the resolution to see the smallest scale structures, cell-like structures with cross-wind scales comparable to mixed layer depth were seen in both scattering intensity and Doppler velocity. The emergence of this technology enables the synthesis of kilometer-long surface current arrays in the open sea, without the cost and logistical support usually associated with large aperture arrays.

INTRODUCTION

We present preliminary results of a new application of acoustic technology. High frequency sound is scattered at low angle from the underside of the sea surface. From the Doppler shift of the backscattered sound, surface velocities can be estimated over ranges in excess of 1.4 km, with roughly 20-m range resolution. Surface gravity waves are evident in these velocity measurements. The velocity measurements can also be time-averaged, to determine low-frequency surface currents and their spatial variability.
In this work, two examples of surface scattering data are presented. Both were obtained on the 1983 Mixed Layer Dynamics Experiment, MILDEX. The first example is a one-hour record showing wave (swell) propagation. A full three-dimensional wavenumber frequency spectrum \( F(k,l,\omega) \) is estimated, using data from two orthogonal sonar beams. The second example presents an eight-hour view of low-frequency surface currents, during a period of particularly strong Langmuir circulation (Langmuir, 1938).

In previous work, the intensity of acoustic returns from surface-scanning sonars has been used to detect surface wave breaking, internal waves and fronts, and even Langmuir circulation (e.g., Thorpe, 1986 and references therein). This is possible because the variations in intensity are related to sub-surface bubble densities, which are modulated by the observable phenomena. In this work, the modulation of surface and subsurface scattering intensity is also clearly seen. New in this work is the ability to correlate the observed intensity fluctuations with the flow field, as estimated from the Doppler shift of the same sonar returns.

THE DATA

During October and November 1983, the Research Platform FLIP was a participant in the Mixed Layer Dynamics Experiment (MILDEX). A number of sensor systems were simultaneously operated in the attempt to observe the mixed layer. The principal sensing systems on board FLIP included fixed and profiling arrays of Vector Measuring Current Meters, operated by R. Weller of Woods Hole Oceanographic Institution; wind, wave, solar radiation, and other environmental sensors; a repeatedly profiling CTD; and six Doppler sonars. The sonars were mounted at a depth of 36 m on FLIP's hull (Fig. 1). They were operated at frequencies between 67 and 80 kHz. Two of the six sonars had nearly horizontal beams while the remaining four pointed downward. A servo controlled thruster, linked to the ship's gyrocompass, was used to maintain the azimuthal orientation of the sensors.

This paper presents data from the two quasi-horizontal sonars. These were oriented at right angles in azimuth. The starboard sonar pointed about one degree up from horizontal on the average. The 75-kHz sound it transmitted scattered from the volume of the mixed layer for the first 500 m of range. Sea surface scattering dominated the return for the subsequent 900 m of sampled range. The port sonar was operated at 80 kHz, and had a mean elevation angle slightly downward from horizontal, much less than 1°. Volume scattering data was collected from the interior of the mixed layer for the first 600 to 900 m. At greater ranges, the beam exited the base of the mixed layer, and profiled the upper thermocline.

The horizontal beamwidth of the sonar is ±1.1°, as measured to the -3db points of the beam pattern. Thus at a "typical" range of 1 km, the surface footprint of each velocity estimate from the starboard (surface grazing)
Fig. 1. a) Schematic and b) plan view of FLIP during the raw data collection. The East sonar grazed the surface, the other remained near 35 m below.
sonar is about 22.5 m (range) by 40 m (across beam). For the port beam, the vertical spread of about 0.44° also enters, yielding a sample volume at 500 m range of about 20 × 20 m horizontally by 4 m vertically, centered somewhere between 25 and 45 m depth (depending on the instantaneous tilt of FLIP).

In operation, each sonar transmitted a sequence of four tones every two seconds. The duration of each tone was 30 ms, corresponding to a 22.5-m averaging range. Velocity estimates were formed using the complex covariance technique of Rummler (1968), using 2-ms lagged covariances. Covariance estimates were averaged over 18 ms in time (13.5 m in range) prior to estimating the velocity. For this signal processing configuration, a "Cramer-Rao" lower bound for error variance in the velocity estimate for a single ping, in the limit of infinite signal-to-noise ratio and uniform scatterer velocity (Theriault, 1986), yields about 3 cm/s RMS error. Using the measured pulse-to-pulse velocity variability of the data, 9 cm/s RMS precision is indicated. However, this includes any real velocity variance within the roughly 20 × 20 m "samples". Twelve-second waves of 0.5 m amplitude were present at the time of the precision measurement. These have steepness (ak) of about 1/70. Averaging over phase, the RMS velocity gradient is then about 1/200 s⁻¹. For an average separation of 10 m, the resulting velocity variance is about 5 cm/s, which is therefore a reasonable estimate of the physical velocity variance. The sum of the physical and lower bound measurement variances is close to the empirical noise estimate.

In operating the full complement of the six sonars, it is necessary to record and process 25 thousand numbers per second. To permit continuous operation of the system over periods of weeks, a CSPI Map 300 array processor is used to form averaged estimates of the covariances in real time over 30-s intervals. However, on the night of 26 October, about an hour's worth of unaveraged data from all six sonars was recorded on tape, filling one tape roughly every 7 min. This was the only segment of such "raw data" recorded during MILDEX, and comprises a "trial sample" for open ocean surface wave detection.

For the eight-hour "Langmuir circulation" segment, the velocity estimates were further averaged over 3 min (90 pings), reducing the RMS statistical noise estimate to about 1 cm/s. In this case, the high frequency variation of surface wave velocities must be considered as a noise source for the mean motion measurement. Worst-case contamination of the 3-min average occurs if there are half-integral numbers of waveperiods in time T = 3 min. Using \( u_{\text{orb}} = a \sigma \sin \sigma t \) and setting \( \sigma = n \pi /T \) where \( n \) is any odd integer, an average over time \( T \) then results in a worst-case of \( u_{\text{contamination}} = 2^{3/2} h / T \), where \( h \) is the RMS displacement of the surface. During the Langmuir circulation segment, the maximum RMS displacement was of order 1 m, leading to worst-case contamination of 1.6 cm/s. The
directional spread, frequency spread, and exponential decay of the orbital velocity with depth would all decrease this aliasing estimate.

In the fluid volume, the dominant scattering targets at 80 kHz are zooplankton. A clear diurnal cycle in scattering strength is seen in all of the volume reverberation data. Surface scattering may arise from either capillary waves at the surface or bubbles just below. The 80-kHz sound used here scatters resonantly from bubbles of about 40 μm radius near the surface, which is near the observed peak in bubble size spectra (Johnson and Cooke, 1979). It is felt that the subsurface bubble cloud is the dominant scatterer (McDaniels and Gorman, 1982; Thorpe, 1986 and references therein). This bubble cloud has been observed to decrease roughly exponentially with depth, with a depth scale which increases slightly with wind, from about 0.4 m for 4 m/s winds (at 10 m height) to about 0.7 m for 10 m/s winds (Thorpe, 1986). For given wind conditions, this depth scale remains nearly constant, although the absolute intensity at a specific depth can vary by about two orders of magnitude (Thorpe 1986). Thus, the depth-scale of the "surface-measurements" shown in the surface wave section may be taken as about a half meter below the instantaneous surface, increasing to about 3/4 meter during the Langmuir circulation segment. Sheltering of parts of the surface from this sonar beam probably occurred occasionally. At the farthest range of 1400 m, the upward angle to the surface from 35 m depth is about 1/40. For 12-s swell (wavelength 225 m) with an amplitude of 0.5 m, as was present during the first (surface wave) segment, the steepness is about 1/70. Thus, the RMS slope was just slightly over half the slope of the beam, and so such sheltering was infrequent during that time period. In this data, the surface-backscattered (starboard) intensity was observed to be about 35 to 40 db greater than the non-surface (port) intensity at the greatest ranges. Thus, although the farthest subsurface ranges are lost to noise, the surface scattering sonar signal remains quite strong over the full 1400 m.

SURFACE WAVES

During the raw data run, FLIP was oriented with the starboard, surface grazing sonar pointing due east and the port sonar pointing due south. The wind was steady at about 4 to 5 m/s from the NNE, and a 12-s swell of about 1 m height (crest-to-trough) was incident from the WNW. Wave propagation away from FLIP is evident in the data from both sonars (Figs. 2 and 3). Also, a range-independent response at the wave frequency exists, due to the movement of FLIP by the swell's orbital motion. This signal was removed from the data shown, for clarity. Notably, the range-independent response is roughly equal in the two beams, whereas the propagating component is attenuated in the South (subsurface) sonar due to the exponential decay with depth of the waves.
Fig. 2. Eleven minutes worth of velocity data from the East sonar. Surface return dominates from about 600 m to 1400 m. Note the wave-like disturbances propagating away from FLIP.
Fig. 3. The same eleven minutes from the South sonar. Beyond about 1 km, the signal strength dropped into noise. Short of 120 m or so, the data is contaminated by side-lobe return. Note the weaker wave propagation, with a cross-hatched appearance due to both Northward and Southward propagating components.
Wavenumber-frequency spectra were calculated for each beam separately, and are shown in Figures 4 and 5. These were formed from 26 sequential data segments each consisting of 64 ranges by 64 pings (864 m by 128 s). The total averaging time is thus about 55 min. At any given frequency, waves incident on a single beam at some angle $\theta$ will produce a signal with an along-beam wavenumber component $|k| \cos \theta \approx \omega^2/g$. In addition, the sonar detects only the component of orbital velocity parallel to the beam, $u_{det} = u_{orb} \cos \theta$. For example, with an isotropic directional distribution of free waves at a given frequency \"$\omega$\", the one-beam wavenumber spectrum would have sharp high wavenumber cutoffs at $k = \pm \omega^2/g$ (at the dispersive values). Also, because only the along-beam component of orbital velocity is detected, the \"raw\" power estimates $|u|^2 \cos^2 \theta$ would decrease relative to the true values $|u|^2$ as the observed component $k_x = |k| \cos \theta$ decreases. Thus, the response-function of the one-beam spectra for free waves at a fixed frequency is a parabola, increasing from zero at $k_x = 0$ to sharp cutoffs at $|k_x| = \pm \omega^2/g$. Bound harmonics, at $2k_x$ and $2\omega$, would also be confined well within these limits.

Fig. 4. Frequency-Wavenumber spectra from the East sonar. Each transverse line represents a set frequency. The two curves crossing the frequency lines represent surface-wave dispersion, $\omega^2 = gk$. Positive k (right) corresponds to eastward propagation (away from FLIP).
Fig. 5. Frequency-Wavenumber spectra, as in Figure 4, but for the South sonar. Positive $k$ (to the right) corresponds to southward propagation (away from FLIP).

The starboard sonar grazes the surface from about 600 m out to 1400 m. The wavenumber-frequency spectrum (Figure 4) was calculated from just these far ranges. The zero wavenumber band was set to zero, to remove the signature of range independent noise associated with FLIP motion. As shown, almost all the detected energy is on the $+k$ half, corresponding to eastward propagation. In addition, the energy is very strongly concentrated near the maximum (dispersion) value, indicating that the swell is propagating very nearly straight down the beam (i.e., from the west). These trial spectra resolve the wave motions to periods as short as 7 s, or 70 m in wavelength. Shorter wavelengths are suppressed by the 22.5-m along-beam smoothing. The influence of linear dispersion is clearly seen.

Swell propagation also appears in the intensity signal of this "surface scattering sonar". To bring this out, a time-averaged intensity at each range is removed, reducing the effects of beam spreading and attenuation with range. A least-squares-fit parabola was then removed at each timestep, to counter the effects of the slight tilting of the beam in the vertical. A sample of the resulting intensity anomalies is shown in Figure 6. In the farther ranges, patterns appear in the intensity signal, which move with the same "phase speed" as in the velocity signal. The middle-ranges are somewhat confused, due to the vertical side-lobe structure of the beam. As an alternate approach, the coherence between East sonar velocity and intensity anomaly was calculated for various wavenumbers (Table 1), averaging over all 1683 pings. To provide a rough estimate of the effective degrees of freedom and hence of statistical significance, the total averaging time
Fig. 6. Intensity anomalies vs. range and time, from the East sonar, as for velocity in Figure 2. Note the suggestion of ripples moving away from FLIP, especially at the far ranges. Surface returns dominate from roughly 600 m out to 1400 m.
(-56.1 min) was divided by the maximum period corresponding to the wavenumber k (i.e., as if the waves were going due east). The most significant correlations, for wavenumbers 3 (\(\lambda = 285\) m) and 5 (\(\lambda = 170\) m) correspond to the brightest spot being located about 65° to 70° toward FLIP from the trough, on the face tilted toward the beam (also the rising face of the waves, since they are propagating away from FLIP). The detected fluctuations in intensity could be independent of wave direction (e.g., if they are induced by variations in scatterer density with wave phase), or could depend on wave direction as does the velocity measurement (e.g., if they are purely an effect of tilting the surface across the beam).

Table 1. Co-spectrum \(<V(k)I^*(k)\>\) of Velocity and Intensity from the East sonar. Phase angle increases toward FLIP from the wave trough (at 0°).

| CYCLES PER 864 m | WAVELENGTH(m) | PHASE(deg) | \(|C|\) | COHERENCE | 68% ESTIMATE |
|-----------------|---------------|------------|--------|------------|--------------|
| 1               | 864           | 12.8345    | .0166  | .0840      |              |
| 2               | 432           | 111.3184   | .0141  | .0707      |              |
| 3               | 288           | 65.1740    | .2351  | .0639      |              |
| 4               | 216           | 50.9758    | .0848  | .0594      |              |
| 5               | 173           | 71.6068    | .1646  | .0562      |              |
| 6               | 144           | 73.2922    | .0910  | .0537      |              |
| 7               | 123           | 79.7480    | .0900  | .0517      |              |
| 8               | 108           | 74.8335    | .0777  | .0500      |              |
| 9               | 96            | 83.3032    | .0685  | .0485      |              |
| 10              | 86            | 77.7762    | .0680  | .0473      |              |
| 11              | 79            | 69.6089    | .0339  | .0462      |              |
| 12              | 72            | 84.0478    | .0226  | .0452      |              |

To demonstrate the potential of this observational system, a full directional-frequency power spectrum \(P(k,\lambda,\omega)\) was estimated (Fig. 7). The method used was a Mills cross technique, as described by Pinkel (1981) for a pair of orthogonal sonar beams. Several aspects of this method should be noted. First, there is a \(\sin\theta\cos\theta\) response: only the radial component of velocity is detected along each beam, and only cross-correlations between beams are used. No estimate is produced along either axis (N or E). This information is contained in correlations along each beam separately, but is neglected in the simple approach used here. In Figure 7, the spectral estimates along the axes were set to zero, and then smoothing in the (k,\(\lambda\)) planes applied. Second, estimates adjacent to each axis are contaminated by noise, due to amplification by the \(1/\sin\theta\cos\theta\) correction for this response. This effect is noticeable in Figure 7A (the highest frequency plane): ridges appear near the axes at higher wavenumbers (though spread slightly by the 3 by 3 smoothing). Third, statistical sampling error leads to larger-than-zero correlations (estimates) along crosses centered on any large "true" power estimate (see, e.g., Fig. 7E). Finally, this is a surface velocity, not elevation, spectrum. A surface wave elevation spectrum with an \(\omega^{-5}\) frequency dependence would correspond to an \(\omega^{-3}\) velocity spec-
Fig. 7. Three dimensional power spectrum, \( F(k, l, \omega) \), from the sonar velocity data. Each surface represents the wave component energies (vertical displacement) at each location on the \((k, l)\) plane, in the frequency band corresponding to periods of (A) 7.1 to 8.0 sec, (B) 8.0 to 9.1 sec, (C) 9.1 to 10.7 sec, (D) 10.7 to 12.8 sec, (E) 12.8 to 16 sec, (F) 16 to 21 sec.
The directional-frequency spectrum shown in Figure 7 is consistent with the visual observations and with the one-beam results. The swell was highly directional, from the WNW. While the peak amplitude in Figure 7 appears in the 13-s to 16-s band, the mean period is closer to 12 s, owing to the sharp low-frequency cutoff and broader high-frequency decay. As frequency increases, the peaks in Figure 7 move toward higher wavenumbers, but also move closer to the East axis. This latter effect is plausibly an artifact of the analysis. The South sonar data was amplified to compensate for exponential decay with depth. Thus, the higher the frequency, the noisier the South sonar data. Finite sampling results in non-zero correlation estimates near the East axis between the amplified noise and the detected (genuine) East-component amplitudes. These are further amplified by the $\sin \theta \cos \theta$ correction. Thus, the true peaks may be further from the East axis than shown in Figure 7.

These trial estimates demonstrate the clear potential of surface-grazing Doppler sonars for estimating directional-frequency spectra of open ocean surface waves. The difficulties discussed above would be reduced by using two surface-grazing beams. With more sophisticated analysis techniques (c.f. Long and Hasselmann, 1979; or Lygre and Krogstad, 1986), greatly enhanced estimates should be possible. Our intent here is to point out the existence and potential of the surface-scanning acoustic Doppler technique for measurement of directional spectra and breaking events.

**LANGMUIR CIRCULATION**

Discussion of Langmuir circulation focuses on data taken between 2000 local time 9 Nov. to 0600 10 Nov. This eight-hour data segment, just prior to the highest winds of the experiment, provided some of the clearest spatial patterns in the Doppler data. During this time, the winds held from the SSW, with half-hour averaged values of 15 to 20 m/s. The surface layer remained well mixed to a seasonal thermocline at 40 to 60 m depth. The RMS wave elevation increased to just over 1 m in this time, with the waves directed predominantly downwind (toward the ESE). The orientation of the wind and FLIP during this time, and the relative positions of the sonar beams and current meters, are shown in Figure 8.

Downwelling velocities exceeding 30 cm/s were observed by Robert Weller of Woods Hole, using his Real-Time Profiler during MILDEX. Values in the range 15 to 30 cm/s were fairly common, especially in this eight-hour period. As described in previous works (Weller et al., 1985; Smith, Pinkel, and Weller, 1987), these downwelling events are associated with surface convergences. The convergence could be easily inferred from the rapid alignment of material on the surface. They often had downwind horizontal velocity fluctuations roughly as large as those in the vertical.
Fig. 8. Plan view of R/P FLIP, showing relative locations of the current meters and sonar beams, and the orientation with respect to the wind during the Langmuir circulation segment.
Thus, the net fluid velocity under the windrows is directed downward about 45° at mid-depth in the mixed layer, relative to the mean velocity of the layer as a whole.

Sonar derived velocities can be compared to point measurements from a Vector Measuring Current Meter (VMCM) which was fixed at 20-m depth during the time discussed here. A vector velocity was formed from the sonar data by averaging over ranges from 100 m to 450 m along each beam, corresponding to sub-surface velocity estimates in both directions. The resulting centers of averaging for the two sonar derived components are separated by about 390 m. In spite of this, the comparison with the 20 m VMCM data is quite favorable (Fig. 9): both the magnitude and direction agree closely. As expected, the point measurements have greater fluctuations about the mean. In both data sets, the fluctuations tend to be asymmetric, with somewhat larger 'squirts' in the downwind direction.

The dominant feature seen in the velocity data is the relative movement of FLIP through the near-surface layer. This is due to the balance of windage on FLIP's superstructure and drag on FLIP's hull, which extends to 90 m below the surface. The downwind velocity of FLIP ranges up to almost 30 cm/s, tracking closely the increasing windspeed over the same time period. The cross-wind velocity changes sign, with the water moving to the left initially (as seen facing downwind from FLIP) and later moving to the right.

To reduce the effects of FLIP's trajectory through the mixed layer and of slow variations in tilt, windspeed, wave height, etc., the data were high-passed filtered. A six-hour running mean was removed, at each range, from both the velocity and intensity data. Backscattered acoustic intensity is discussed in terms of dB (10 log10) relative to this time mean at each range. Removing the time-mean intensity reduces greatly the effects of beam spreading and attenuation. Tilting combined with mean vertical shear can introduce large-scale velocity 'noise' along each beam; thus, the spatial mean, trend, and wavelengths 480 m and longer (up to 3 cycles in 128 times 11.25 m) were also removed at each time-step. The resulting data are shown in Figure 10. FLIP's position is along the bottom edge of each square. The data segment is eight hours long, resolved in 3-min intervals. Black represents larger than average values, white less than average. The full height of each contour plot represents 1400 m in range, with 11.25 m by 3 min pixels. Again, the port sonar data (Figs. 10a,b) corresponds to averages over roughly 25 to 45 m depth by about 20 m across beam (at 500 m range), by 22.5 m in range. This will also be referred to as the "downwind" or "x" beam. The starboard sonar beam (Figs. 10c,d) reflects off the sea surface at ranges greater than 600 m. It corresponds to an average over a surface area of 22.5 m by approximately 20 m at 600 m, increasing to 40 m width at 1200 m. The vertical scale depth of the near-surface scattering layer is about a half meter. This "surface scattering beam" will also be referred to as the "crosswind" beam.
Fig. 9. The VMCM record from 20 m depth (bottom; in cm/s), the 'mean sonar velocity' obtained by averaging from 100 to 450 m along each beam (3rd row; cm/s), the wind (2nd; in m/s), and FLIP's orientation (top row; the length of these sticks are arbitrarily set to 10 units).
Fig. 10  (a) Shaded contours of high-pass filtered downwind velocity over the period of 2200 9 Nov. to 0600 10 Nov. Contour interval is 1.0 cm/s. (b) \( I_x \), the high-pass filtered downwind intensity fluctuations. Contour interval is 0.5 db. The diagonal stripes represent regions of anomalous intensity (black = bright, white = dim), which appear to approach FLIP. Due to windage and shear across the thermocline, FLIP is moving downwind (toward these "lumps") at about 20 cm/s, in good accord with the angle made by these stripes. (c) \( dV_y/dy \), the high-pass filtered crosswind convergence rate. Contour interval is 0.0009 s\(^{-1}\). (d) \( I_y \), the crosswind intensity variations. Contour interval is 0.25 db. The 6-beam returns from the surface about 600 m out to 1400 m from FLIP.
The movement of FLIP downwind through the water relative to nearly stationary features produces steep, straight "streaks" in the downwind-data and curved ones in the crosswind. The reversal in the crosswind advection of features is evident near 0200 of the 10th. Referring to the stick-plot comparison between the sonars and 20 m VMCM (Fig. 9), this 'reversal' actually represents a relatively small rotation of the total velocity (relative to FLIP) across the downwind direction.

The downwind beam reveals features in both velocity and intensity which appear to approach FLIP from the greatest detectable range (about 1 km) to the nearest (100 m) in roughly one and one half to two hours (Figs. 10a,b), corresponding to a mean downwind-velocity of about 20 cm/s relative to FLIP. Typical amplitudes of these fluctuations are about ± 5 cm/s for high pass filtered velocity intensity and ± 2.5 db in I_x. In this period, just prior to the peak winds observed during MILDEX, the bulk flow relative to FLIP increased from 16 to 23 cm/s, so the speed of the streaks visible in both intensity and velocity are consistent with advection by this bulk flow. Also, very faint and broad scale modulations appear in the x-velocity data at about 35°, "propagating" downwind (away) faster than FLIP (Fig. 10a). One possible explanation is that the cross-wind velocity of about 5 cm/s could advect elongated stationary features sideways across the downwind beam; thus, long features ("streaks") oriented at various angles about the wind could have virtually any apparent "propagation" speed, yet be quasi-stationary in the water. Another (and quite likely) possibility is that internal gravity waves, propagating in the seasonal thermocline, are responsible for the streaks. The internal wave explanation can be rejected for the smaller, steep streaks on the grounds that these propagate too slowly relative to the mean flow. The converse is not true: long stationary features advected at an angle can have any apparent phase speed, and so cannot be rejected even for the broad, "propagating" features observed here.

In the crosswind direction, the surface divergence dV/δy is shown (Fig. 10c), rather than high-pass filtered velocity. The observed features in ∂V/∂y and I'_y (Fig. 10c,d) appear to reverse direction somewhere near 0200, again consistent with advection by the mean flow (Fig. 9). The typical amplitudes are ± 2.5 db in I'_y, and ± 0.003 s^-1 for the convergence rates.

If the features were long enough in the downwind direction and lasted long enough, they could be observed for longer than the two hours it took to progress the entire length of the other beam. However, the features can be traced for only about two hours, as before. We conclude that the individual features are limited to either two hours duration or to the 1-km to 2-km length scale covered by FLIP in that time. The features may persist longer, or have longer extent alongwind, but not both. The crosswind length scale (half the distance between convergence zones) is in the range 50 to 80 m; thus, the features appear to be about 10 to 20 times longer in the downwind direction than in the crosswind.
These crosswind convergence data are interesting in that they reveal the evolution in time of the crosswind scales of the flow. To examine this, wavenumber spectra of surface convergence rates were formed using data from ranges 700 to 1400 m (surface return). The spectra are plotted at 2-h intervals over the two days surrounding the maximum winds, from 1800 8 Nov. to 1800 10 Nov. (Fig. 11). Each spectrum shown is an average of 40 realizations, each calculated from a 3-min average of the sonar data. A best-fit quadratic in range was removed from each 3-min sample prior to Fourier transformation. The eight-hour "close-up" segment is bounded by heavier lines.

A low-wavenumber "cutoff" in crosswind convergence appears on the evening of the 9th, as the activity at higher wavenumbers increases. The peak just above this cutoff progresses from about 100 m wavelengths near 2000 to about 150 m by 0400 of the 10th, intensifying as the scale grows. During this time, cards thrown on the surface aligned into rows with a much smaller spacing, due to activity at higher wave-numbers. In the presence of multiple scales, visual observation of cards on the surface leads to a bias toward the smaller scale windrows, due to the relatively short observation times and distances. In contrast, the sonars are able to detect a maximum spacing scale under these circumstances. Thus, correspondence of this maximum scale to other environmental factors (e.g., mixed layer depth) can be explored more reliably with the sonar data than previously possible. Over the same time period, the mixed layer depth increased from roughly 40 to 60 m depth (Fig. 12). The maximum spacing between convergences remained close to three times the mixed layer depth over the whole period. In subsequent days, the mixed layer thickness oscillated with about a 12-h period, a consequence of the baroclinic tide. We conjecture that the largest scale circulations 'tracked' the mixed layer depth as long as the wind was strong, adjusting relatively quickly to a maximum streak spacing of nearly three times the layer thickness.

SUMMARY

During a period of fairly gentle 12-s swell, a surface-grazing Doppler sonar was used to observe surface wave propagation along a nearly 1-km path. The sonar sampled the motions every 2 s, with 22.5 m range resolution. Propagating surface waves were seen in the Doppler velocity estimates, and also, to a lesser extent, in the backscattering intensity. A weak maxima in scattering intensity appeared to occur on the forward faces of the waves.

Three-dimensional wavenumber-frequency spectra were estimated using the Doppler output. The trial spectra resolve the wave motions to periods as short as 7 s, 70 m wavelength. The influence of linear dispersion is clearly seen. Considerable improvement can result by using two (or more) surface-scattering sonar beams, rather than one surface and one sub-surface
Fig. 11. 2-h mean power spectra of crosswind surface convergence, dV/dy, at 1-h intervals from 1800 8 Nov. to 1800 10 Nov. Note the appearance of a peak between 1800 (7) and 2200 (6) of the 9th, progressing to lower wavenumbers with time. Peak wavelengths designated are (7 cycles) = 103 m, (6) = 120 m, (5) = 144 m, and (4) 180 m.
Fig. 12. The mixed layer depth showing the near-tidal frequency oscillations occurring during and after the eight-hour segment chosen for close examination of Langmuir Cell activity.
beam, as here. Also, more sophisticated analysis techniques should produce greatly enhanced estimates. Our intent here is simply to point out the existence and potential of a surface-scanning acoustic Doppler technique for measurement of directional spectra and breaking events.

During a separate period of moderate to high winds, the sonars detected lower frequency organized motions, which appear to be Langmuir cells. As surface convergence zones in this eight-hour 'close-up' period passed through the sonar beams, individual features (streaks) were observed. These features, identified through both velocity and intensity fluctuations, were roughly static with respect to the mean velocity of the layer, and persisted for up to two hours. In this time, FLIP drifted downwind about 2 km relative to the water, implying that these features stretched over 2 km parallel to the wind. The half-wavelength across the wind was about 60 to 90 m. The features were thus about 20 times as long as wide. The maximum crosswind spacing between convergences stayed close to three times the mixed layer depth, while that depth varied from about 40 to 60 m.

An ideal sonar for this type of work would transmit a fan-shaped beam broad in the vertical plane, narrow in azimuth. With fan shaped beams, pitch and roll of the transducer affect the output very little. Only yaw, variation in azimuth, needs to be suppressed. Thus, surface current measurements from sub-surface moorings or from slowly moving ships is a possibility. The intensity variations can also be used to observe breaking events and the subsequent decay of the resulting bubble cloud (Thorpe, 1986; Vagle and Farmer, 1986), providing a useful supplement to the current field and surface-wave directional information.

The prospect of being able to measure surface wave propagation continuously over distances greater than a kilometer, to get a measure of breaking activity (bubble formation), and to sense the surface currents which interact with the wavefield and with the mixed layer all with a single instrument encourages further study and development.

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