The San Clemente Ocean Probing Experiment: A Study of Air-Sea Interactions with Remote and In Situ Sensors

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Abstract

A multifaceted experiment was performed in September 1993 by the NOAA Environmental Technology Laboratory (ETL) near San Clemente Island, 100 km offshore of San Diego, to investigate environmental effects on microwave scattering and emission from the sea surface. The experiment, called the San Clemente Ocean Probing Experiment (SCOPE), employed simultaneous measurements of X-band radar cross section and of atmospheric parameters that govern the radar scattering cross section such as atmospheric surface-layer stability, wind, and friction velocity. These measurements were made simultaneously with surface wave measurements from the Scripps Institute Floating Instrument Platform (FLIP), measurements from an airborne microwave radiometer, and images from airborne and satellite-borne synthetic aperture radars.

Preliminary results indicated the following: (1) surface currents are potentially measurable to a precision of a few centimeters per second with the Δk radar technique; (2) disturbances on the marine inversion may occasionally cause strong modulations of radar images of the ocean at low grazing angles; (3) horizontal polarization was much more effective than vertical at depicting ship wakes; and (4) an atmospheric boundary layer (ABL) eddy forms in the lee of the island as observed by the ETL Doppler lidar; surface manifestations of the eddy are apparent in the island-based X-band radar and in synthetic aperture radar (SAR) images of the ocean surface. First looks at data from the newly developed array of pressure transducers revealed interesting transitions of the wave field, wave packet signatures, and standing wave patterns.

THE EXPERIMENT

Atmospheric parameters such as stability, wind, and friction velocity all strongly determine the way in which the ocean scatters and emits microwave energy. Therefore, in order to assess quantitatively the complex air-sea interactions taking place, it is sensible to measure backscatter and emission in the context of simultaneous measurements of surface-layer parameters along with measurements of the wave fields themselves. SCOPE was therefore designed with this concept in mind. X-band normalized radar cross section (NRCS) measurements were made at both horizontal and vertical polarizations from a high site on San Clemente Island (SCI) with a low grazing angle view of the ocean through an azimuth sector from 270° clockwise to 130°. The view included the positions of FLIP and a NOAA research vessel on which in situ sensors monitored the water and atmospheric surface-layer parameters. Figure 1 shows the radar position (circle) on SCI and the position of FLIP (triangle) 32 km to the NW of the radar. Depths below mean sea level are in meters, and a portion of Catalina Island is shown about 50 km north of the radar. The research vessel Titan was directed to different positions within view of the radar depending on radar echoes that were displayed in real time.

One of the main objectives of SCOPE was to further our understanding of different scattering and emission mechanisms at horizontal and vertical polarizations. To accomplish this objective, various radar data-taking modes were performed: azimuthal scans of the ocean were made with and without HH/VV polarization switching, at grazing angles ranging from about 10° to 0.5°, and in different directions relative to the wind/wave field. Often, scans were performed in synchrony with the collocated Doppler lidar to observe the effects of surface-layer wind on radar backscatter. The radar was frequently operated with the antenna fixed to collect stepped-frequency Δk data as well as standard "pulse-to-pulse" data for Doppler spectral processing. These observations were made while simultaneous atmospheric and oceanographic measurements were made from FLIP and Titan.

SCOPE INSTRUMENTATION

New instrumentation prepared for SCOPE included a coherent X-band Δk radar with variable polarization and pulse width. The radar was operated from a high site (573 m) on San Clemente Island and was collocated with a CO2 Doppler lidar for remote measurements of wind just above the surface. A newly developed array of pressure transducers for gravity wave measurements and a microbarograph array for atmospheric surface-layer pressure measurements were operated from FLIP. Also on FLIP was an atmospheric surface-layer package developed at ETL to measure surface-layer stability, wind, and friction velocity; a similar package was also deployed on the R/V Titan, provided by the NOAA Corps. A 915-MHz wind profiler and radio acoustic sounding system (RASS) for temperature profiling was operated on the Titan as well as on SCI to probe the deeper ABL. Microwave and infrared (IR) emission were observed from a NOAA King Air aircraft recently instrumented by ETL with microwave and IR radiometers. One flight was obtained over the area with the JPL AirSAR, and there were three overpasses with the ERS-1 SAR during SCOPE operations, two of which are discussed here.
INITIAL RESULTS

Figure 2 shows a summary of surface observations made from FLIP for 12 days during SCOPE. Starting at the top, the figure shows sea surface temperature/air temperature, solar radiant intensity, wind direction/speed, and friction velocity. The figure shows that the surface layer was unstable for the duration of SCOPE, that winds were predominantly from 330°, and that winds were not strong, averaging around 4 m s⁻¹ with a maximum wind of about 11 m s⁻¹ on one brief occasion. Swell was usually light and from the same direction as the wind.

A common observation during SCOPE, though not completely understood at this time, was for NRCS to be equal at horizontal and vertical polarizations, referred to as HH and VV, respectively, when looking upwind/upwave (toward 330°), but for VV to exceed HH by about 10 dB in the opposite direction. The 10-dB difference downwind is consistent with Bragg scattering, but the equality of NRCS in the upwind direction contradicts the Bragg hypothesis. In addition, corresponding Doppler measurements show equal Doppler velocities downwind (where NRCS differences are the greatest), and upwind velocities obtained at HH being 0.5 to 1 m s⁻¹ greater in magnitude than at VV. These relationships are shown in Fig. 3 with the top frame showing NRCS at HH (solid) and VV (dashed) for range samples between 16.5 and 17.5 km, as a function of azimuth. The fluctuations near -30° are from land blockage and ground clutter at the 2° depression angle in that direction. The velocity and NRCS measurements downwind are compatible with Bragg scattering since the equality of velocities suggests that the same (Bragg) scattering elements are responsible for both polarizations. The differences in velocities upwind suggest that scattering elements contributing to VV are different and spatially separate from that of HH. However, the equality of NRCS in that direction seems to be too coincidental to be consistent with the different scatterer hypothesis. In summary, we conclude, with some uncertainty, that downwind scattering appears Bragg-like and upwind appears non-Bragg-like.

Radar echoes that are not explainable by conventional ocean scatter were observed on several occasions as shown in Fig. 4. Such observations, repeated every minute, suggest that the wavy nature of the image is not caused by ocean waves: (1) there was no detectable movement of the 2-km-wavelength pattern for 10- to 15-min periods during which the pattern retained coherence, and (2) the velocity field was featureless with no corresponding wave pattern in evidence. We suggest that standing waves on the marine inversion in the lee of SCI caused periodic variations in the grazing angle and/or focusing and defocusing of the radar beam. At low grazing angles, small angle variations produce large variations in NRCS. Similar results were seen in both polarizations.

The Δ-k radar technique has been used to estimate wave slope spectra and to measure ocean surface currents (Plant and Schuler, 1980; Johnson et al., 1982). In essence, the technique utilizes the transmission of two microwave frequencies separated by a few megahertz to a few tens of megahertz to establish a fringe pattern that resonates with capillary wave patterns on the surface. Waves having wavelengths from about 5 m to 50 m can induce the required capillary wave patterns through the mechanisms of exposing wave crests to greater wind than troughs, through tilt modulation, through straining and velocity modulation by swell, and through other mechanisms; small-scale wind gusts tend to destroy such patterns. The selected frequency difference determines the gravity wave to be interrogated and should be chosen to correspond to the dominant wave, if possible.

As implemented for SCOPE, the ETL radar in its Δ-k mode transmitted ramped sequences of frequencies that were stepped by 3 MHz from pulse to pulse through a total of 12 steps. The 11 frequency pairs possible with this sequence allowed 11 gravity waves from 4 m to 50 m wavelength to be sampled. Since the dominant wavelength was not known a priori, all 11 frequency pairs were considered in our initial examinations of the data. Current information is obtained from the cross-product power spectrum, which is the square of the Fourier transform of the product of the complex amplitudes received at two frequencies. Under good signal-to-noise conditions, a narrow spike near the frequency of the selected gravity wave is found in this spectrum. Deviations from the expected zero current position of the spike are caused by currents that can then be retrieved. An example of one such spectrum is shown in Fig. 5. The accuracy to which the position of the spike can be determined suggests that currents can be measured to within a few centimeters per second over an area of about 10⁴ m² with this technique.
Figure 4. Radar image of NW quadrant observed at vertical polarization. Shading indicates NRCS in decibels, and range rings are every 5 km. Depression angle was 2°.

Figure 5. Cross-product power spectrum for a 12-MHz frequency difference (12.5-m-wavelength) at a range of 6.75 km. Current estimated from this spectrum is 4 cm s⁻¹.

SAR images were obtained from two ERS-1 overpasses during SCOPE. These two cases provided contrasting scenarios in that differing wind conditions generated a definite eddy in the lee of SCI in one case and no eddy in the other. Evidence of the eddy is readily apparent in the SAR image shown in bottom half of Fig. 6 for September 15, 1993, while other image for August 30, 1993, does not indicate an eddy. The eddy, seen as calm water (white) to the east of the island, was caused by wind from WSW flowing around the steep topography of SCI that has a maximum elevation of nearly 600 m. The eddy was not apparent when wind was from the WNW as in the top frame. X-band radar images of ocean surface also indicated weak echo in the calm water in the lee of SCI for the eddy case and uniformly high echo otherwise. On other occasions, the radar observed distinct Doppler velocity discontinuities with as much as a 2 m s⁻¹ difference observed over a distance less than 100 m. This was also believed to be caused by a clockwise circulation in the ABL to the lee of the island.

Figure 6. ERS-1 SAR images of ocean near SCI showing absence of MBL eddy (top) on August 30, 1993, and manifestation of eddy (bottom) on September 15, 1993.

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REFERENCES
