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INSTABILITY WAVES OBSERVED ON THE EQUATOR IN THE ATLANTIC OCEAN DURING 1983

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Abstract. A packet of surface confined westward propagating waves apparently generated by barotropic instability of the surface currents was observed in the equatorial Atlantic during 1983. Initial wavenumber analyses and energetics calculations are presented. Local working by the horizontal Reynolds stress was large enough and at the correct time to account for the wave packet's existence. The amplitude of the waves was comparable to the mean currents implying that the waves are of primary importance in the momentum balance of the seasonally varying equatorial surface currents.

Introduction

Large scale meanders of the surface South Equatorial Current (SEC) and the subsurface Equatorial Undercurrent (EUC) were first described by Düing et al. (1975) using measurements made in the equatorial Atlantic during July-Sept. 1974. Westward propagating oscillations with a periodicity of around 16 days were observed. Weisberg (1979) showed that these were confined primarily to the surface region. Using infrared satellite imagery, Legeckis (1977) pointed out similar surface features in the eastern equatorial Pacific Ocean and this analysis was expanded upon by Legeckis et al. (1983) to include data from 1975-1981. Summer and fall seasons showed westward propagating oscillations with a mean period and zonal wavelength of 25 days and 1000 km respectively. Halpern (personal communications) has observed similar seasonal behavior in moored current meter records from that region. Waves occurred when the equatorial surface currents were westward.

Deep expressions of these surface meanders have also been observed. Weisberg et al. (1979), using moored current meter data from below the thermocline in the eastern equatorial Atlantic Ocean, identified a packet of equatorially trapped Rossby-gravity waves with central periodicity of 31 days and westward and upward phase propagation with length scales of 1200 km and 1000 m respectively. Further analyses by Weisberg and Horigan (1981) suggested that these waves were seasonal with their origin in the central equatorial Atlantic during July-Aug. Indications of oscillations with around 30 day periodicity in the deep equatorial Indian Ocean shown by Luyten and Roemmich (1982) further suggest that these features are universal to equatorial oceans.

Barotropic instability between the westward SEC and the eastward North Equatorial Countercurrent (NECC) appears to be the origin of the meanders. Analytical and numerical calculations by Philander (1978) and Cox (1980) respectively show narrow band instabilities with both rapid growth rate and the observed scales. Waves are seasonally generated as the SEC and NECC intensify in response to seasonally varying wind stress.

During the first year of the SEQUAL experiment a packet of the above waves was observed in current meter records from five surface moorings: three along the equator near 28°W, 24°W, and 15°W, and two along 28°W near 45'N and 45'S. Initial analyses of the wave packet are presented with emphasis on phase propagation and energy flux. Supporting data from surface ship observations are given by McPhaden et al. (1984).

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Data

Table 1 lists mooring positions and instrument depths for Vector Averaging (VACM) and Vector Measuring (VMCM) current meters on surface moorings from Feb.-Sept. 1983. North components of velocity at the 10 m level from the three positions along 28°W and at the equator, 15°W are shown as examples in Figure 1. A wave packet appears around mid-May at 28°W and somewhat later at 15°W. The packet exists over 2-3 cycles with a central periodicity of 25 days. Oscillations appear primarily in the north component (v) as opposed to the east component (u) or temperature and their amplitude diminishes rapidly with depth.

Kinematics

Frequency domain empirical orthogonal function analyses were performed about a central frequency of 4.0×10^{-2} cpd as determined from spectral analyses of all time series. Cross-spectral matrices, each element computed with approximately 17 degrees of freedom as determined from record length and bandwidth, were constructed and their eigenvalues and eigenfunctions calculated. This was done horizontally for v at each separate depth and vertically for both v and u at the equatorial 28°W mooring. The eigenvalues partition variance into orthogonal modes and the eigenfunctions give the spatial distribution of amplitude and phase for each mode.

First mode results for v as a function of horizontal position at each depth are shown in Figure 2. With the exception of the 150 m level, the first mode contains 85%-90% of the variance within the band. Phase propagation is consistently westward with data points closely grouped about a mean zonal wavenumber component of -5.5×10^{-3} rad/km (1140 km wavelength) corresponding to a phase speed of -53 cm/sec. Motions are in phase meridionally along 28°W and the amplitudes are fairly uniform at each depth.

First mode results, including 84% and 55% of the variance of v and u respectively, are shown as a function of depth in Figure 3. The amplitude of v exceeds that of u at all depths and it

Table 1. Mooring positions and instrument depths for current meter records from Feb.-Sept. 1983.

	0°44'N 28°11'W	0°00'N 28°09'W	0°45'S 28°10'W	0°03'N 28°59'W	0°01'S 14°57'W
10m	VACM	VACM	VACM		VMCM
50m		VACM		VACM	VACM
75m	VACM	VACM	VACM	VACM	VACM
100m	VACM	VACM			
150m	VACM	VACM	VACM	VMCM	VMCM
200m		VACM			

decreases precipitously below 50 m. Phase is fairly uniform for v while it varies for u. This results in a nearly in phase relationship between v and u over the upper 50 m with an attendant non-zero Reynolds stress versus a nearly $\pi/2$ phase difference below 50 m suggesting that the Reynolds stress is zero below the surface layer.

Energetics

Contrary to the wavenumber analysis resulting in westward phase propagation, inspection of the data, e.g., Figure 1, suggests eastward energy flux. To assess this, the v time series were complex demodulated about a 25 day periodicity using the same bandwidths as in the wavenumber analysis. The resulting envelopes for the wave packet are shown in Figure 4. The upper curves are from the 50 m level at the three zonal positions along the equator. Eastward movement of the packet is clearly seen. The middle curves are from the 10 m level at the three meridional positions along 28°W. No meridional energy flux is observed. The lower curves are from the 10 m, 50 m, and 75 m depths on the equatorial 28°W mooring. Downward energy flux is evident.

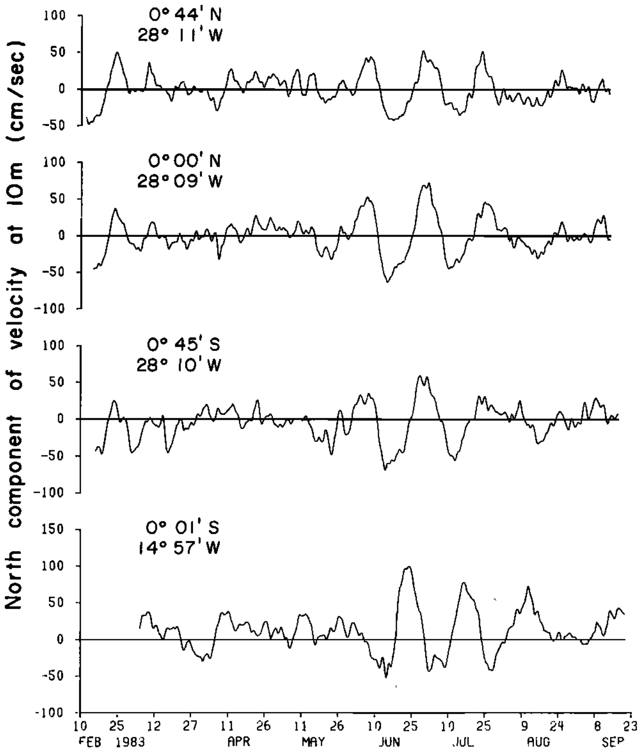

Fig. 1. Low pass filtered north component time series at a depth of 10 m.

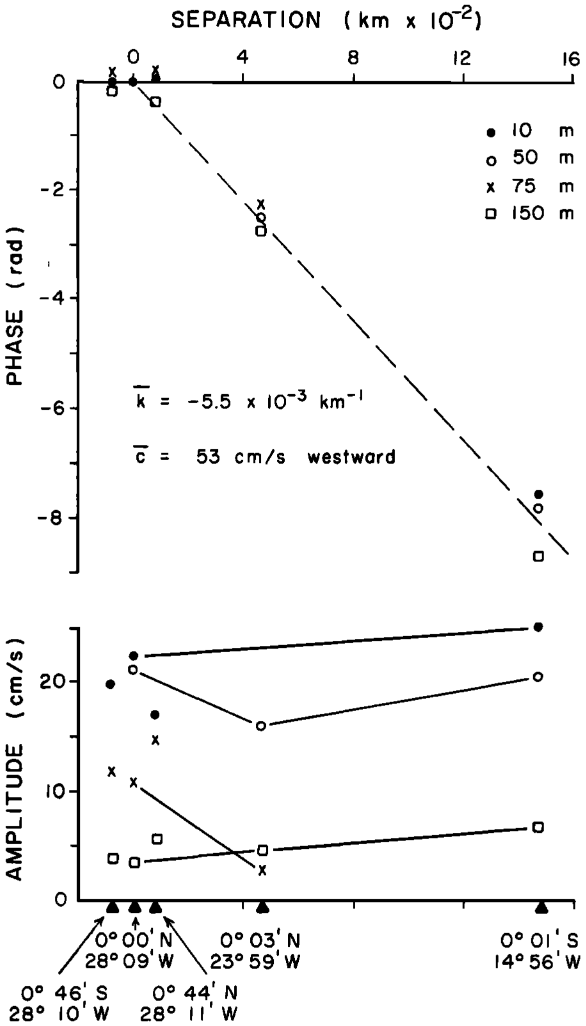

Fig. 2. Amplitude and phase of the first empirical orthogonal mode as a function of horizontal position computed for north components at each individual depth. Central frequency and bandwidth for the calculations are 4.0×10^{-2} cpd and 4.4×10^{-2} cpd respectively.

The apparent zonal component of group velocity may be estimated from the lag times between different zonal positions along the equator. This is shown in Figure 5 using both cross-covariances and modal times at 10 m and 50 m. A mean value of 124 cm/sec is obtained. Similarly the apparent vertical component of group velocity is estimated at -8.7×10^{-3} cm/sec.

Whence does the wave packet derive its energy? If barotropic instability is the mechanism then

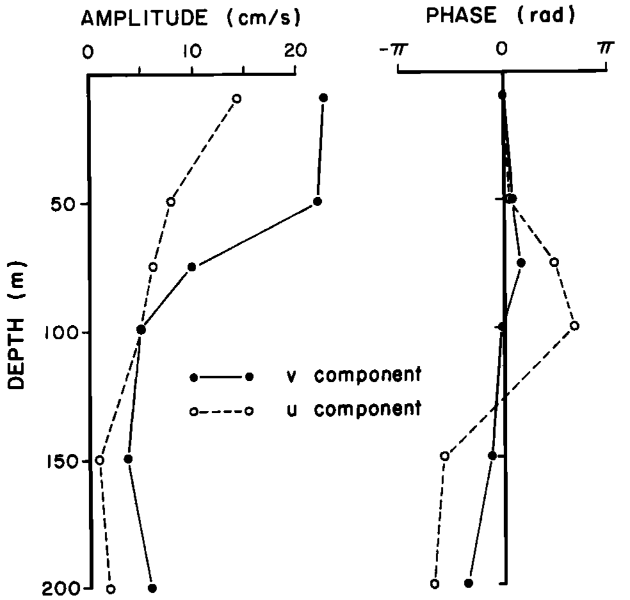

Fig. 3. Amplitude and phase of the first empirical orthogonal mode as a function of depth at 0°00'N, 28°09'W computed for north and east components. Central frequency and bandwidth for the calculations are 4.0×10^{-2} cpd and 4.4×10^{-2} cpd respectively.

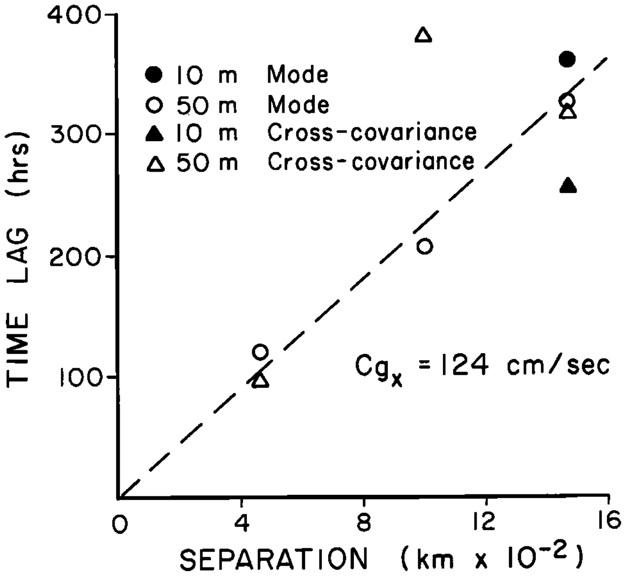

Fig. 5. Time lags for the wave packet envelopes as a function of zonal separation for north components at depths of 10 m and 50 m. Lags were obtained from both cross-covariances and modal times.

the production term $-\rho\overline{u'v'}\ \partial U/\partial y$ is important, where $\rho\overline{u'v'}$ is the horizontal Reynolds stress and $\partial U/\partial y$ is the mean meridional shear of the zonal current system. Positive values of the production term indicate fluctuation energy derivation at the expense of the mean currents. Figure 6 shows Reynolds stress time series at the equatorial 28°W mooring calculated as 25 day running means. Since $\partial U/\partial y$ was observed to be negative, positive Reynolds stress is required for energy transfer from the mean currents to the waves. At the 10 m level the Reynolds stress is zero until the beginning of June. It is then positive for one month reaching a peak during mid-June. The timing of this Reynolds stress pulse matches the wave packet very closely with the Reynolds stress peak corresponding to the maximum rate of change of the packet envelope and the end of the pulse corresponding to the maximum packet amplitude. Integrating the Reynolds stress pulse times $\partial U/\partial y$ obtained between 45'N and the equator shows that local production is more than adequate to account for the kinetic energy of the wave packet. Below 50 m the Reynolds stress reduces to zero showing that most of the production is above the thermocline.

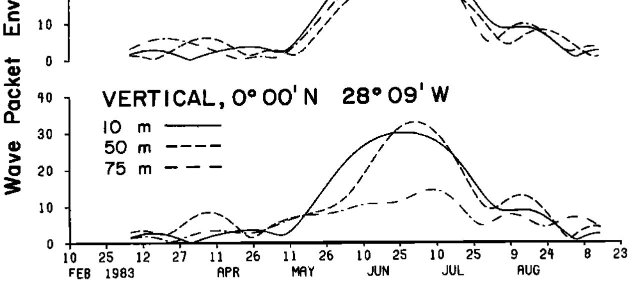

Fig. 4. Wave packet envelopes as a function of time at different zonal, meridional, and vertical positions calculated by complex demodulation about a central frequency of 4.0×10^{-2} cpd with a bandwidth of 4.4×10^{-2} cpd.

Summary

Part of the seasonal cycle in the equatorial oceans is the generation of waves with time scales of around 3 weeks and length scales of around 1000 km. A packet of these waves was observed during the first year of the SEQUAL experiment lasting 2-3 cycles with central periodicity of 25 days and zonal wavelength of 1140 km. Phase propagation was westward at around 53 cm/sec while the packet envelope (apparent group velocity) progressed eastward and downward at around 124 cm/sec and 8.7×10^{-3} cm/sec respectively. No indications of meridional phase or energy propagation were evident and wave energy fell rapidly below 50 m. Horizontal Reynolds stress time series along with the meridional shear of the zonal currents suggested that local wave energy production by barotropic instability was large enough and at the correct time to account for the wave packet's existence. Reynolds stress time series were in phase meridionally and vertically but progressed eastward zonally. It is

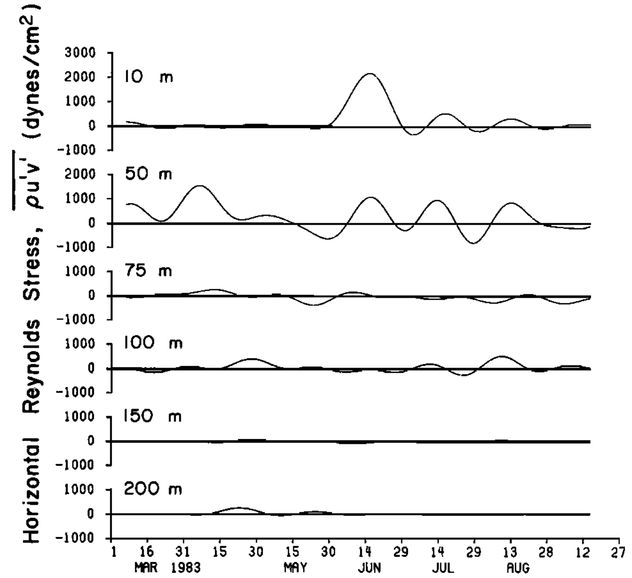

Fig. 6. Reynolds stress time series for all depths at 0°00'N, 28°09'W computed as a running mean over 25 days.

unclear whether the apparent eastward energy flux results from propagation or local generation by an eastward progressing instability. Analysis of the combined SEQUAL/FOCAL data sets along with numerical model experiments may aid in this interpretation. Since the amplitude of these waves at the ocean surface is comparable to the magnitude of the mean currents, the waves are of primary importance in the momentum balance of the seasonally varying equatorial surface currents.

It is also interesting to note that with a slight shift to lower frequency, the packet observed here is nearly identical in zonal wavelength, phase speed, packet dimension, and timing to the Rossby-gravity wave packet previously observed below the thermocline in the eastern equatorial Atlantic as mentioned in the introduction. The equatorial waveguide does serve as a conduit for some of the wave energy generated near the surface; just how much will be a topic of continued study.

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