Observations of Topographic Rossby Waves on the Continental Margin off Nova Scotia

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ABSTRACT

Bursts of topographic-Rossby-wave energy have been observed in data recorded by an array of current meters moored on the outer continental shelf and slope off Nova Scotia north of the Gulf Stream. The waves persist for three or four cycles during which both the period (10 to 23 days) and the amplitude of the oscillations are modulated. At least four different events have been observed over approximately one year and appear to be associated with warm eddies shed by the Gulf Stream. One particularly clear event, dealt with in detail, had a period of 21 days, an offshore scale of 175 km and an offshore phase speed of 8 km day^{-1}. The array of moorings was too small to resolve accurately the longshore scale or propagation direction. The wave appears to be barotropic (nearly uniform in amplitude and phase) at the 1000 m isobath, but increasingly baroclinic in both cross-slope directions. Deep-water kinetic energy associated with the wave appears to be uniformly distributed over the upper portion of the rise.

1. Introduction

The theoretical expectation that the vorticity constraints provided by variations in $f\ h^{-1}$ throughout the ocean basins support topographic Rossby waves has been discussed by numerous authors (e.g., Rossby, 1945; Veronis, 1966). Near the continental margins, vortex stretching due to the rapidly changing bottom topography dominates the planetary β-effect and topographic waves prevail. The trapping and guiding of these topographic waves has been discussed extensively by Rhines (1969). In addition, intense western boundary currents, such as the Gulf Stream, have been suggested by some authors as possible generators of topographic waves in these areas. In recent years there has been increasing evidence that the low-frequency quasi-geostrophic current fluctuations observed over some continental margins are indeed related to topographic Rossby waves.

On the basis of an extensive spectral analysis of the current records from site D (39°10′N, 70°00′W, 2600 m deep), Thompson (1971, 1977) and Thompson and Luyten (1976) conclude that there is evidence for propagating topographic waves below the thermocline. They find most of the subtidal kinetic energy in the low-frequency bands (periods of 8–64 days), with a strong concentration around 16 days and an apparent high-frequency cutoff near eight days, consistent with linear theory. They also conclude, supported by Luyten (1977), that the momentum flux associated with these oscillating currents is into the Gulf Stream, while the energy flux is out of it. This lends support to the conjecture that the observed waves may result from forcing in the region of the Gulf Stream.

Kroll and Niiler (1976) have used a barotropic model on piecewise-continuous exponential topography to investigate the effects of the observed topographic Rossby wave impinging on the New England continental margin. Their results indicate that much of the incident energy would be reflected from the steep continental slope and thus produce a strong standing oscillation over the slope and rise. Furthermore, the amplitude of the wave is greatly enhanced on the slope as energy is concentrated in the shallower regions. On the other hand, Rhines (1971) suggests that more gradually shoaling topography or the effects of isobath curvature might cause significant refraction rather than reflection of the incoming rays. This might also lead to a significant buildup of wave energy in the shallow regions, but would not produce the offshore modulation of the kinetic energy that characterizes the standing wave. Rhines also suggests that, because of the highly dispersive nature of these waves, a search for events in the raw data may provide more insight into the dynamics of these oscillations. In either case, there is reason to expect high levels of topographic wave energy on the upper slope near the shelf break.

Petrie and Smith (1977) and Smith (1978), using spectral methods, have noted features of the low-frequency current variability over the Scotian Shelf and Slope which suggest the presence of topographic waves (e.g., an offshore momentum flux in the 10–30 day band). The limited extent of those data pre-

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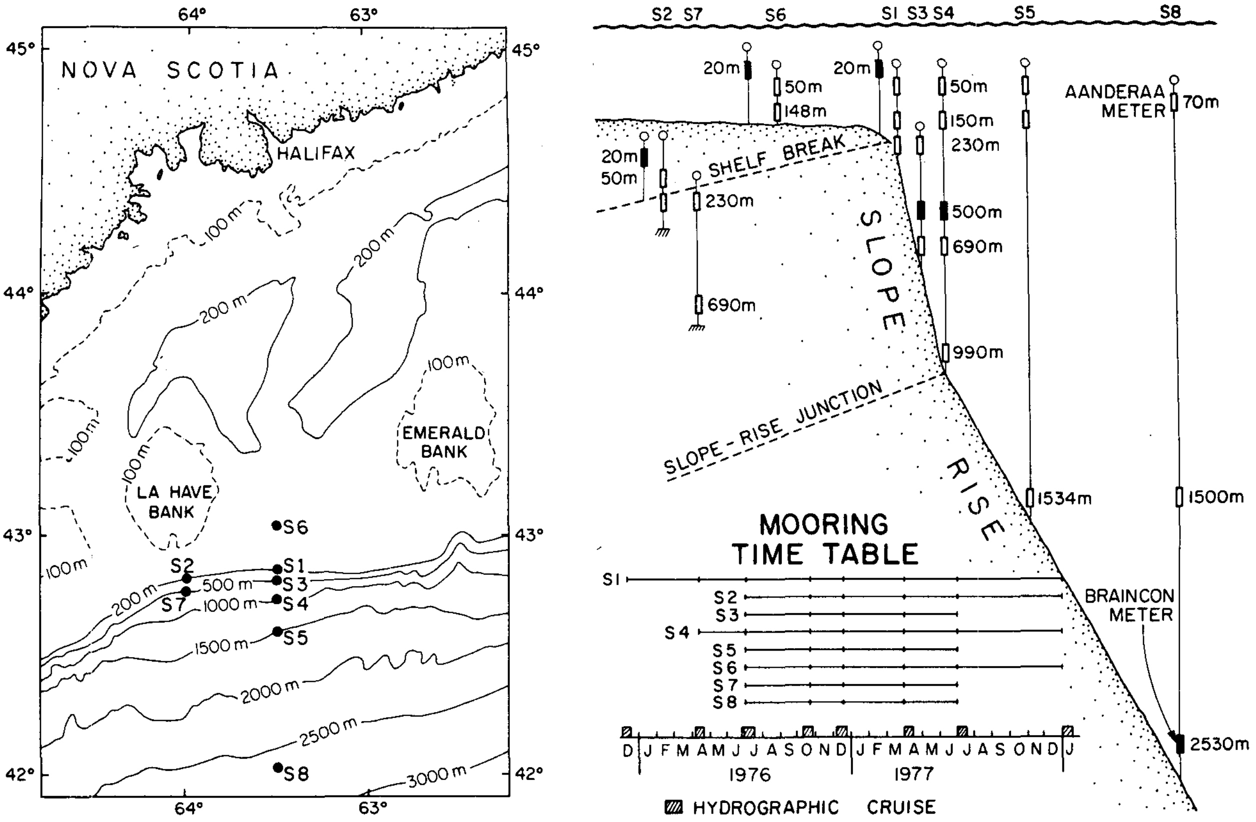

FIG. 1. Schematic diagram of the Shelf Break Experiment.

cluded quantifying the spatial and temporal scales of these oscillations.

To investigate these and other low-frequency processes, scientists at Bedford Institute began a two-year observation program at the shelf break south of Halifax in December 1975. The mooring array is shown in Fig. 1. During the course of the experiment a number of low-frequency events occurred that were spatially coherent throughout much of the array. This paper describes one such event, which took place during the summer of 1976, a period during which there was good spatial and temporal coverage. The temporal and spatial scales, current amplitude, vertical and horizontal kinetic-energy variation, and the frequency of events throughout the entire two years of the program will be presented. A simple kine-

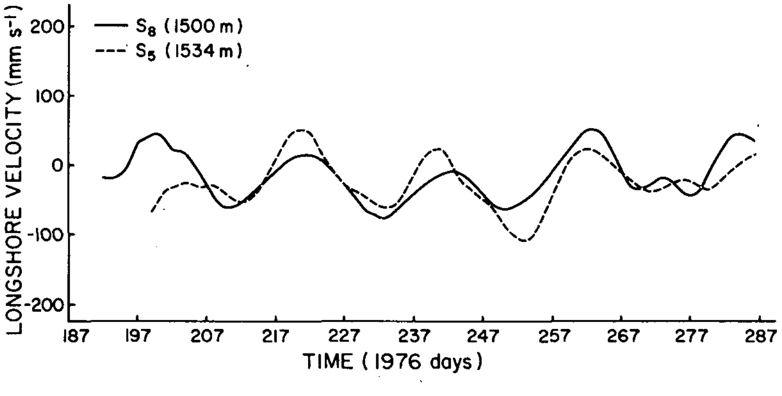

FIG. 2. Low-passed records of longshore current at S8 (150 m) and S5 (1500 m) during July-October 1976. The S8 record has been lagged by seven days.

matical interpretation will be offered; a detailed model is developed in a companion paper (Louis and Smith, 1982).

2. The low-frequency records of longshore velocity

Current meter data were low-passed with a Cartwright filter (half-power point at 31 h) and subsampled at 6 h intervals to remove tides and high-frequency motions. To focus on topographic-wave oscillations in the current field, the 6 h records were further smoothed using a Cartwright filter with a high-frequency cut-off of 0.10 cpd (half-power point at period of 7 days). The low-passed records of longshore current from July–October 1976 show a distinct wavelike event with a period of roughly 21 days and amplitude of 50–100 mm s^{-1}, which lasts for 4–5 cycles. Fig. 2 shows the longshore components at S5 (1534 m) and S8 (1500 m), which are separated by 53 km in the offshore direction. The record at S8 has been lagged by seven days to reveal the clear correlation between the two signals. With a period of 21 days, this phase difference implies an offshore wavelength of ~160 km and offshore phase speed of about 8 km day^{-1}. More extensive analysis in the next section will confirm that the phase difference indeed represents a seven day lag, not a 14 day lead.

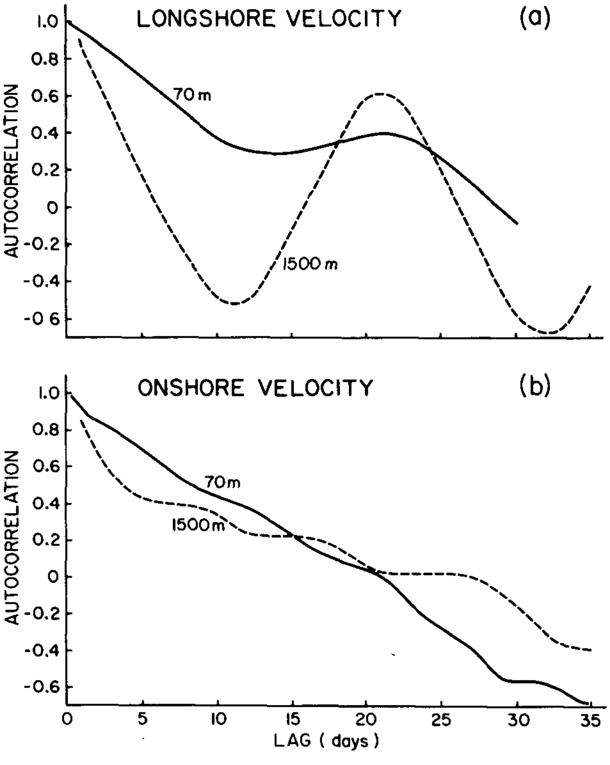

FIG. 3. Autocorrelation functions for (a) longshore and (b) onshore velocity components calculated from the 6-h data at S8 (70, 1500 m) during July–October 1976.

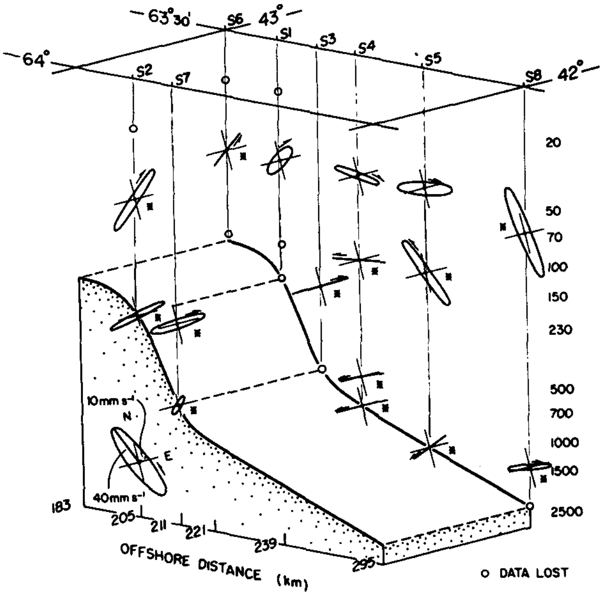

FIG. 4. Current ellipses for the 21-day band of the rotary spectra during July–October 1976. Depth scale is logarithmic and the ellipses are oriented with respect to the E–W axis. Arrows indicate sense of rotation for the current vector, and an asterisk signifies the presence of a distinct 21-day oscillation in the low-pass longshore current record or autocorrelation function.

It is of interest to note that the peak-to-peak amplitudes of the two records are comparable, although the total depth at the S8 site is ~1000 m greater than that at S5. The longshore velocity records at most of the other stations throughout the array show oscillations similar to those at S5 and S8.

After accounting for the offsets in the temporal origins, a close comparison of the two records in Fig. 2 indicates that the energy in the 21-day oscillation appears at S8 somewhat earlier than it does at S5. It is worth noting at this point that sea-surface temperature data revealed the formation of an eddy ("Eddy I")[2] from a Gulf Stream meander due south of the array, just prior to the start of the current-meter records. A more complete analysis of this event and its relationship to the current measurements is presented by Louis and Smith, 1982.

The autocorrelation function for the velocity components at S8 (Fig. 3) defines the dominant time scales of the events occurring during this period. The 21-day oscillation is strikingly evident in the longshore component at 1500 m, but is obscured near the surface (70 m) by the generally higher level of baroclinic noise above the thermocline (Rhines, 1971). Typically, no trace of the 21-day wave appears in

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[2] The identification of sea surface temperature anomalies (e.g., eddies) follows that used on the "Experimental Ocean Frontal Analysis" (EOFA) charts, U.S. Naval Oceanographic Office, Washington, DC.

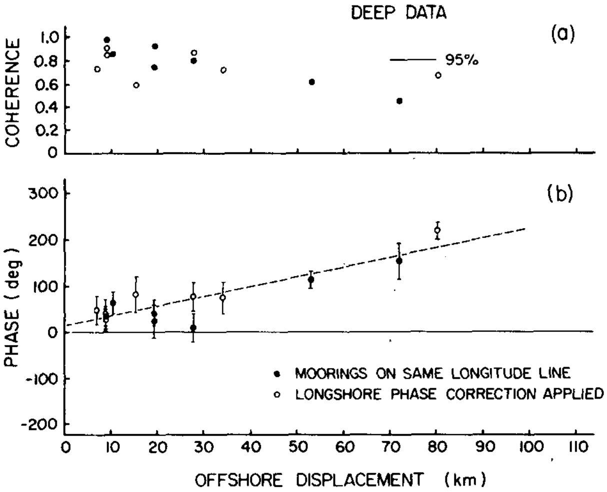

FIG. 5. Coherence and phase between "deep" (≥150 m) longshore current measurements from the shelf break array during July–October 1976. Positive phase indicates offshore propagation. Closed circles represent values from moorings on same longitude line, whereas open circles correspond to data from moorings on different longitudes to which a longshore phase correction has been applied. The linear regression for the phase estimates (dashed) indicates offshore propagation at 2.1°km^{-1}.

the onshore component, but a much longer period oscillation (70–80 days) is evident, particularly at 70 m. This longer time scale, which also appears in the longshore component at 70 m, may be related to the lower-frequency fluctuations in the shelf/slope-water boundary and the baroclinic radiation field associated with Eddy I.

Fig. 4 presents a summary of the 21-day wavelike oscillations over the mooring array in terms of the current ellipses in the fundamental band (centered at 0.0469 cpd) of the rotary spectra. An asterisk next to the ellipse indicates the presence of a strong 21-day oscillation in either the low-passed record or the autocorrelation function for longshore current. It is clear from this diagram that the motion, in the deep water at least, is rectilinear and oriented at a small angle to the direction of local isobaths, which strike north of east by (8°, 15°, 15°, 14°) at (S4, S5, S7, S8).

3. Spectral estimates of length scales

The coherence and phase between "deep" (depth > 70 m) longshore current records (Fig. 5) provide statistical estimates of wavelength and phase speed associated with the 21-day oscillations. The coherences (computed from four blocks of 21.3 days), though high, are probably somewhat degraded by the large bandwidth (0.0469 cpd) and the small number of degrees of freedom in the estimates. The slope (2.1 ± 0.9° km^{-1}, the latter value is the standard error of the slope at the 0.05 level) of the least-squares regression for all of the phase estimates indicates an offshore wavelength of 175 km and a phase speed of ~8 km day^{-1}, which are in good agreement with the visual estimates of the previous section. The intercept (17 ± 32°) of the regression contains the origin in its confidence limit.

The linear trend (2.1 ± 1.0° km^{-1}) in the phase estimates from the "shallow" (50 m) records (Fig. 6) is essentially the same as that for the deep data. The intercept is −0.2 ± 15°, which includes the origin. Coherences are generally lower because of the higher levels of background noise in the surface records.

In the alongshore direction, the coherences be-

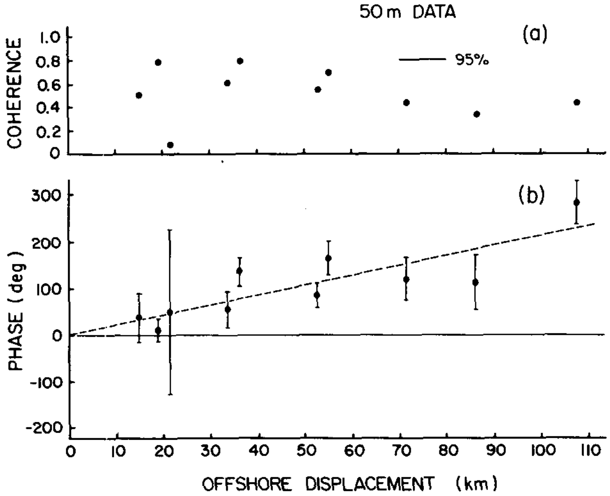

FIG. 6. Coherence and phase between "shallow" (50 m) longshore current measurement from the shelf break array during July–October 1976. Positive phase indicates offshore propagation and the linear regression for phase estimates (dashed) represents an offshore phase speed of 2.1°km^{-1}.

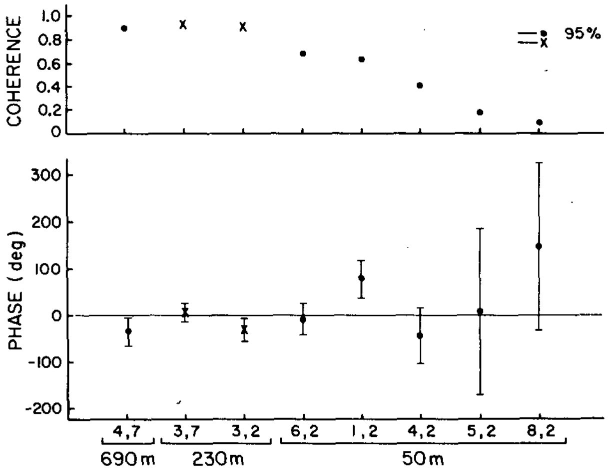

FIG. 7. Coherence and phase between longshore current measurements on 63°30′W and 64°W during July–October 1976. Positive phase indicates "westward" propagation. Phases of the records from different isobaths have been adjusted by an amount equivalent to an offshore phase speed of 2°km^{-1}.

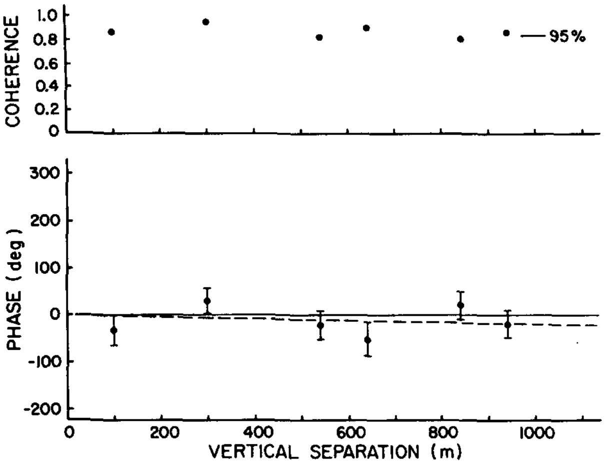

FIG. 8. Vertical coherence and phase between longshore current records at S4 during July–October 1976. Positive phase indicates upward propagation and the linear regression for the phase estimates represents downward propagation at 1 km day^{-1}.

tween longshore current records on 63°30′W and 64°W (Fig. 7) are significant at the 95% level in the deep water (>50 m), but generally lower at 50 m and fall off sharply with the distance between the stations. To account for offshore propagation, the phase estimates for records from different isobaths have been adjusted by an amount equivalent to an offshore phase speed of 2° km^{-1}. Nevertheless, no significant trend may be detected in the alongshore phase differences. Equal numbers of the estimates imply eastward and westward propagation and most of the error bars include zero. All that can be reliably inferred from these data is that the longshore wavelength is very large and that the 40.5 km alongshore separation of the mooring lines is too small to resolve it.

The S4 mooring was the only one on the slope or rise with sufficient resolution to examine vertical scales. All but one of the vertical coherences (Fig. 8) in longshore current at S4 were significant at the 95% level. The phase differences for all pairs are shown also. The least-squares regression for the phase estimates relative to the 50 m data indicates a vertical wavelength of 20 km and a downward propagation of approximately 1 km day^{-1}. However, the value of the correlation coefficient was low (−0.37), which lending little confidence to these estimates. Furthermore, nearly all the error bounds on the phase estimates include zero, indicating that the behavior is nearly barotropic over the 1 km water column at S4.

Inspection of the low-passed records of longshore velocity at S4 (Fig. 9) confirms the result of the cross-spectral analysis that the vertical phase shifts are small. The variable phase differences that are observed, between 50 and 990 m for example, may be qualitatively accounted for by slow variation of the onshore current at 50 m, which affects the net phase speed at that level (i.e. it Doppler-shifts the signal) relative to the bottom where the onshore component is almost zero. In addition, the similarity in amplitude between the 21-day oscillations at 50 and 150 m, on the one hand, and those at 690 and 990 m, on the other, shows little evidence for bottom trapping. It also is evident from Fig. 9 that the period (i.e., the time between successive peaks and troughs) of the current oscillation is changing. In fact, starting at the peak around day 200 the time intervals between successive peaks and troughs are 12.0, 16.6, 18.3, 19.2 and 21.7 days, respectively, for the 990 m data. Such a large change in period was not evident in the 1500 m data (Fig. 2) from moorings further down the rise. The time intervals appear to shorten after day 250. Finally, note that the deep records clearly reveal the burstlike character of the wave energy. The amplitude of the low-frequency waves at 690 and 990 m grows steadily from the start to roughly day 240, then declines sharply over the final third of the record.

Baroclinic noise is also indicated in the records by the strong vertical shear, which develops between the near-surface (50, 150 m) and deeper instruments near day 250 and coincides with the observation of

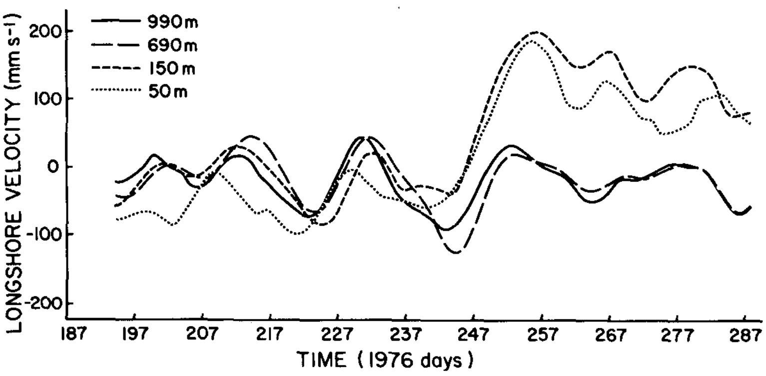

FIG. 9. Low-passed records of longshore current at S4 (50, 150, 690, 990 m) during July–October 1976.

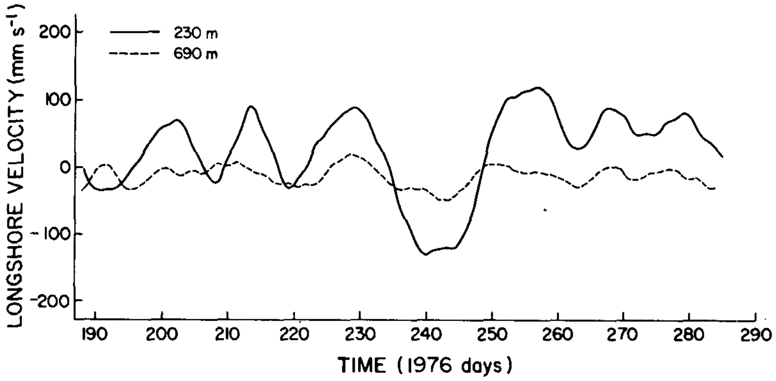

FIG. 10. Low-passed records of longshore current at S7 (230, 690 m) during July–October 1976.

Eddy K (EOFA charts, U.S. Naval Oceanographic Office) in sea-surface temperature data. The apparent location of the center of this feature between moorings S5 and S8 is confirmed by the simultaneous occurrence of strong pulses of longshore current (eastward at S5, westward at S8) on these moorings. As with the measurements at S4, these nonlinear effects are confined primarily to the surface layers above the main thermocline, where, in conjunction with the variable Doppler shifting, they are probably responsible for degrading the coherence and phase estimates associated with the shallow data.

Although the vertical uniformity in phase observed at S4 appears to be a ubiquitous feature, at least in the deep waters of the slope and rise, the same cannot be said for the amplitude of the 21-day oscillation. On the 700 m isobath, for instance, the longshore current records at S7 (Fig. 10) reveal a distinct amplification of the wave at 230 m (relative to the oscillations at S4), accompanied by a severely reduced signal near the bottom. The 230 m longshore current (Fig. 10) shows an increasing time interval between successive peaks and troughs from days 200 to 250, as was seen in Fig. 9. The change to shorter-period oscillations towards the end of the record may coincide with the appearance of Eddy K. The variations in 21-day energy density over the mooring array are further explored in the next section.

4. Spatial variation in energy density

Because of the variable orientations of the current ellipses, especially in the surface layer (Fig. 4), the total kinetic rather than longshore current energy density in the 21-day spectral band will be examined in this section. In the deep water, the distributions of these two quantities are quite similar because of the dominance of the longshore component. All available estimates of kinetic energy at 21 days during summer 1976 are presented in Fig. 11 as a function of offshore distance. Interpretation of this diagram is difficult because the large bandwidth (0.0469 cpd) represented in the spectral estimates allows energy from a wide range of periods (Figs. 9 and 10) to be included with the 21-day wave. The baroclinic noise in the surface layers (50–150 m) is particularly evident on the offshore moorings, S5 and S8. In fact, there appears to be a continuous decline of the near-surface energy in the onshore direction over the rise, reaching a minimum at S4 where, as already mentioned, the energy distribution is nearly uniform vertically.

The horizontal distribution of deep (≥230 m) kinetic energy over the rise, on the other hand, is relatively uniform. In particular, there appears to be little evidence for offshore structure, such as the spatial modulation caused by the standing component associated with a significant reflected wave, or the upslope amplification (inversely proportional to depth) suggested by the barotropic theory of Kroll and Niiler (1976). On the continental slope, however, the deep energy is strongly baroclinic, as typified by the S7 data (Fig. 10), and the amplification at 230

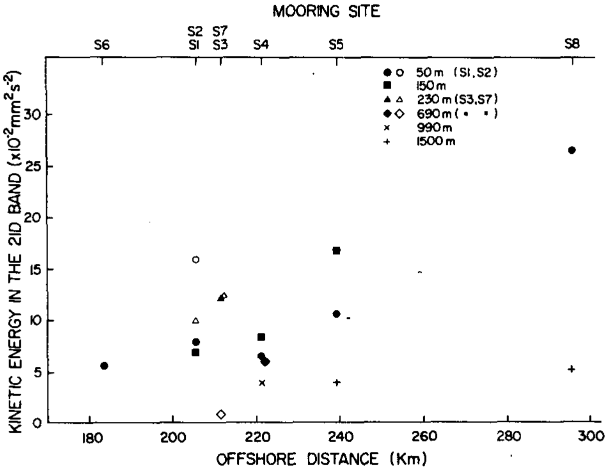

FIG. 11. Spectral estimates of kinetic energy in the 21-day band from the shelf-break mooring array during July–October 1976. Moorings S1, S2 lie near the shelf break on the 240 m isobath.

m appears to also be present at the shelf break. The deep measurements at S3 and S7 consistently show very low energy levels, indicating a node of the 21-day oscillation on the topography at the 700 m isobath. Farther onto the shelf at S6, the 21-day kinetic energy declines.

5. Interpretation

Existing theoretical models of topographic Rossby waves are basically of two types: barotropic waves over simple topography and baroclinic waves in a stratified medium on very small slopes. Despite serious deficiencies and omissions in their representations of the real ocean, both models qualitatively account for the observed features of the 21-day oscillations. Simple examples are given below using the original authors' notation as transformed to a coordinate system with x increasing offshore and z increasing upward.

Rhines (1970) derives a pressure solution to linearized equations for a stratified fluid with a rigid lid and gently sloping bottom, and gives the dispersion relation as

$$\sigma = -\frac{l\alpha N}{K_H}\coth\frac{NK_HH_0}{f_0}, \tag{1}$$

where k is the offshore wavenumber, l the longshore wavenumber, α the slope, H_0 the local depth, N the Brunt-Väisälä frequency, and f_0 the Coriolis parameter, and $K_H{}^2 = k^2 + l^2$.

This solution is valid for small values of the slope parameter: $\delta_s \equiv \alpha L/H_0 \ll 1$, where L is the horizontal scale of the wave ($K_H{}^{-1}$). For characteristic values appropriate to the Scotian Rise [$H_0 = 2$ km, $L = (2\pi/175)^{-1} \approx 30$ km, $\alpha = 2 \times 10^{-2}$, $f_0 = 1 \times 10^{-4}$ s^{-1} and $N = 2.6 \times 10^{-3}$ s^{-1}], the slope parameter ($\delta = 0.3$) is marginally small, and the Burger number, $B = \{NH_0/Lf_0\}^2$, which measures stratification effects, is order one. Substituting $\sigma = 3.5 \times 10^{-6}$ s^{-1} and $K_H = 3.5 \times 10^{-5}$ m^{-1} into the dispersion relation (1) yields $l = -2.3 \times 10^{-6}$ m^{-1}, or a longshore wavelength of 2800 km. The major axis of the theoretical current ellipse is rotated clockwise from local isobaths by 3.7° and the bottom trapping scale f_0/NK_H (≈ 1 km) is of the same order as the depth. These properties are consistent with the 21-day band measurements and, in particular, lend support to the observation of a barotropic oscillation at S4.

Veronis (1966) describes a barotropic model for topographic Rossby waves over exponential topography, $h = h_0e^{\mu x}$, and derives a dispersion relation

$$\sigma = -\frac{f\mu l}{k^2 + l^2 + \mu^2/4}. \tag{2}$$

For a reasonable value of μ (2.5×10^{-5} m^{-1}), along with the other physical constants and observed wave scales, this model predicts the longshore wavelength, $2\pi\, l^{-1} = 3500$ km, the phase velocity, $c_p = (9, -170)$ km day^{-1}, and group velocity $c_g = (-1.5, -170)$ km day^{-1}, that is, the energy propagates basically alongshore and slightly up the Scotian Rise. For small longshore wavenumber, the major axis of the ellipse is rotated clockwise by $-kl(\mu^2/4 + k^2)^{-1} = 2.5°$ from local isobaths and the ratio of major to minor axes is $-2(k^2 + \mu^2/4)/\mu l = 57$. Hence, the character of the rectilinear barotropic oscillation agrees qualitatively with both the observations and the results of the stratified model. [Note that with $\mu = \alpha/H_0$, (1) and (2) approach the same limit, $\sigma = -\mu fl/K_H{}^2$, as NK_HH_0/f_0 and μ/K_H approach zero, respectively.]

Clearly, neither of these simple models is equipped to analyze the effects of abrupt changes in topography, such as the slope–rise junction or the shelf break itself. Kroll and Niiler (1976) have patched together barotropic solutions over three adjoining exponential slopes in order to model flow on the New England continental margin. Application of their model to the waters off Nova Scotia indicates that ~80% of the incoming wave energy would be reflected by the Scotian Slope, producing a strong standing oscillation over the slope and rise. The lack of evidence for such a reflected component in the observed offshore distribution of kinetic energy and the essentially longshore-energy flux predicted by the barotropic model support Rhines' (1971) suggestion that low-frequency topographic Rossby waves are refracted rather than reflected by the steeply sloping topography of the continental slope and rise.

Louis and Smith (1982) have attempted to model the generation of topographic waves by a Gulf Stream ring (Eddy I) by solving the barotropic initial value problem for (i) a point source of vorticity, (ii) a dipole source, and (iii) an isolated circular vortex on the continental rise. Their results indicate that the asymptotic radiation field on the upper rise consists of a modulated dispersive field of waves with characteristic periods of 10–20 days. In addition, refractive effects are assessed using a WKB approximation for realistic topography.

6. Observations from other periods

In the foregoing subsections, low-passed records of longshore current and spectral estimates in the 21-day band have been used to reveal the character of topographic-wave oscillations over the Scotian Rise and Slope during summer 1976. The energy appears in the current records as a coherent burst of 4–5 cycles, the beginning of which coincides with the formation of Eddy I south of the array. Bursts of low-frequency energy in longshore currents in conjunction with offshore eddy events have also been recorded at other times during the Shelf Break Experiment. Table 1 gives details of the start times, observed periods, duration, and associated eddies for

TABLE 1. Low-frequency oscillations detected at S1 (220 m) and S3 (230 m) during the Shelf Break Experiment: July 1976–December 1977.

Start (day/year)	Range of periods (days)	Duration (cycles)	Associated feature in sea-surface temperature (eddy identification)*	Season
180/1976	12–23	4	I	summer
300/1976	11–19	3	K	summer/fall
56/1977	10–14	3	M	winter
110/1977	12–22	4	Q_1	spring
227/1977	12–15	4	Q	summer

* EOFA charts, U.S. Naval Oceanographic Office.

the oscillations recorded at S3 (230 m) and S1 (230 m). During the fall and winter seasons these events compete with the higher-frequency fluctuations associated with the wind-driven circulation, and the seasonal spectra exhibit significant leakage of this energy into the fundamental band. For the spring and summer of 1977, however, the offshore distributions of the 21-day kinetic energy in the surface and deep layers may be compared to those for summer 1976. In the surface layers (Fig. 12a) the offshore energy increase is reproduced in both seasons, and the horizontal and vertical uniformity of deep energy over the rise is evident in spring 1977 (Fig. 12b). In addition, the strong baroclinic effects over the slope, indicated by the "error bars" on the deep-water estimates at S3 and S7, are found again in spring 1977. Thus the burst of 21-day wave energy is a ubiquitous feature of the low-frequency spectrum on the continental slope and rise off Nova Scotia.

7. Summary and conclusion

A detailed examination of low-passed current records has revealed a series of bursts (3–4 cycles) of low-frequency (periods 10–25 days) energy occurring throughout the experiment. In a particularly clear example of this phenomenon in July–October, 1976, autocorrelations for deep records of alongshore current depict a strong 21-day oscillation, and estimates from the 21-day spectral band indicate an offshore wavelength and phase speed of 175 km and 8 km day^{-1}. These scales, plus the vertical uniformity of phase and kinetic energy observed at the 1000-m isobath (S4), are consistent with simple models for topographic Rossby waves. However, the measured alongshore phase differences are not distinguishable from zero, so the dispersion relation cannot be fully tested. In the deep layer at S4, the amplitude of the waves is strongly modulated: growing steadily for roughly 50 days of the record, then declining rapidly, to produce the observed burst of 21-day energy.

The barotropic nature of the oscillation at S4 is destroyed in both the onshore and offshore directions. Offshore, over the continental rise, the surface layer (50–150 m) energies are greatly enhanced by nonlinear, baroclinic noise, as observed off New England by Thompson (1971). The tendency toward vertical uniformity with increasing distance from the (offshore) source is a feature of the transient radiation fields described by Tang (1979), in which the slow expansion rate (≈ 1.5 km day^{-1}) for baroclinic waves is given by the planetary β parameter times the square of the internal deformation radius, so that the "fast" barotropic waves dominate the far field. According to his model, the upslope penetration of the baroclinic effects would also be limited by the steepening slope near S4. In the deep offshore waters, the horizontal uniformity of the 21-day kinetic energy suggests that most of the barotropic wave energy is refracted rather than reflected from the steep continental slope (Rhines, 1971).

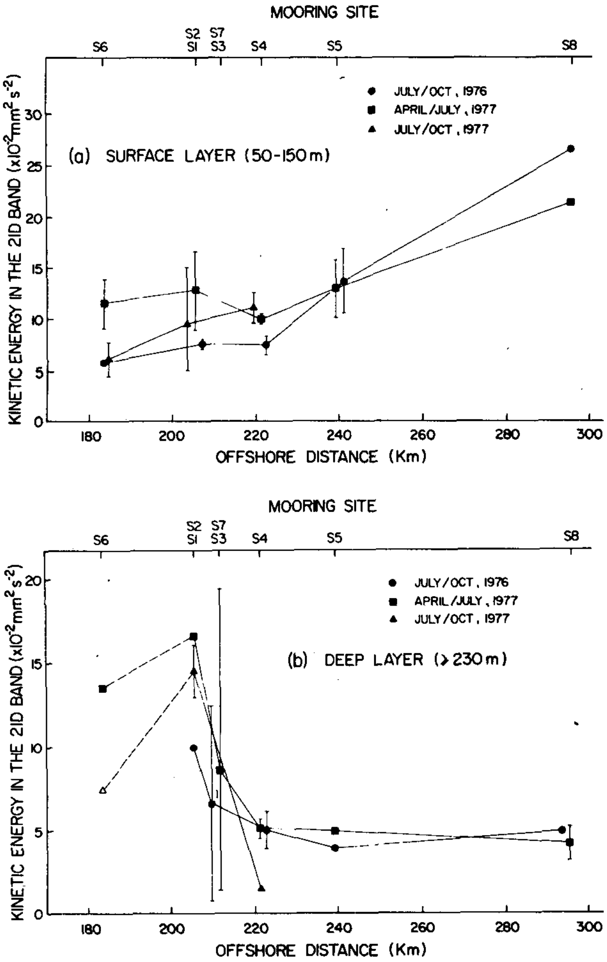

FIG. 12. (a) Average of spectral estimates for 21-day kinetic energy in the surface layers (50–150 m) from the shelf break array during summer 1976, spring 1977, and summer 1977. Error bars represent the range of estimates at 50, 150 m. (b) Average of spectral estimates for 21-day kinetic energy in the deep-water layers (≥ 230 m) from the shelf-break array during summer 1976, spring 1977, and summer 1977. Error bars represent the range of estimates from 230 m to the bottom.

Shoreward of the 1000 m isobath (over the slope) the 21-day oscillation is again strongly baroclinic, featuring large amplification of the waves at 230 m and reduced energy near the bottom. This behavior suggests that part of the incoming energy may be scattered into baroclinic modes trapped to the steep topography as described by Ou and Beardsley (1980).

Finally, it appears that the recorded bursts of topographic wave energy during the Shelf Break Experiment are associated, in some way, with interactions between the Gulf Stream or its eddies and the waters south of the array. For example, the 21-day oscillation examined in this paper appears to have been generated by Eddy I. The relationship between the topographic wave events and eddy activity, as well as refractive effects of the Scotian Slope and Rise topography are examined in a companion paper in this issue (Louis and Smith, 1982).

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