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Shelf Edge Processes

by

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ABSTRACT

Abstract depth changes which characterize the edges of continental shelves lead to interesting and inportant physical processes in the ocean. Progress in understanding three such processes:

1) the interaction of offshore currents and eddies with the continental margin,
2) wind-driven upwelling at the shelf break, and
3) the generation of internal tides and nonlinear waves by the M_2 surface tide,

is reviewed. Two possible modes of interaction between offshore currents and coastal waters are contrasted. The first is characterized by direct forcing of eddy exchange by a current guided along the shelf edge (as on the Labrador and Newfoundland shelves or in the U.S. South Atlantic Bight) while the second features remote forcing by low-frequency topographic Rossby waves radiated from offshore meanders and rings to the shelf edge. In addition, wind-driven upwelling from depths of 400 m or more is shown to result from moderate by persistent longshore wind. However, the complex bathymetry of the shelf may cause anomalously high currents in a fully three-dimensional circulation. Finally, large-amplitude internal waves driven by the M_2 surface tide are shown to be a ubiquitous feature of the shelf edge circulation. The intense vertical mixing associated with these phenomena promotes high levels of biological productivity at the shelf edge by continuously supplying nutrients to the surface layers.

1. Introduction

Abrupt depth changes which characterize the edges of continental shelves lead to interesting and important physical processes in the ocean. The associated steep bottom slopes are responsible for guiding low-frequency currents along isobaths; for refracting, reflecting and scattering of various wave motions; and for promoting the upwelling of deep ocean waters to the shelf. On the western sides of major ocean basins, strong boundary currents, such as the Gulf Stream or Labrador Current, radiate low-frequency energy that impinges on but rarely crosses the continental margin because of vorticity constraints associated with the large change in depth.

Other important energy sources for shelf edge phenomena include the barotropic (surface) tide and surface wind stress. In addition, the reduced thermal capacity of shallow shelf seas relative to the deep ocean and the input of fresh water runoff to the shelf may lead to sharp contrasts between coastal and oceanic water masses at the shelf edge. These strong gradients, combined with energetic physical processes, generally lead to enhanced mixing and biological productivity. Off the southeastern coast of the United States, for instance, the upwelling of deep water at the shelf break caused by wind and eddy activity along the inshore edge of the Gulf Stream is considered to be the major source of nutrients to the shelf ecosystem (Atkinson *et al.*, 1982). Similarly, Fournier *et al.* (1977) suggest that shelf-break processes are responsible for the observed maxima of biological rates and standing stocks at the edge of the Scotian Shelf. Even in the absence of forcing by energetic offshore currents, as on the Northwest European Shelf, eddy activity associated with the shelf-break front may promote high rates of cross-shelf mixing (Pingree, 1979) while vertical mixing by internal waves injects nutrients into the euphotic zone.

In the following sections, attention will be focussed on studies of three different varieties of shelf edge processes:

a) the interaction of offshore currents and eddies with the topography of the continental margin,

b) wind-driven upwelling at the shelf break, and

c) the generation of internal tides and nonlinear waves by the M_2 surface tide.

Each section will give a brief account of the historical development of understanding of the particular phenomenon. On the continental shelves, as in many areas of oceanographic research, advancement does not occur steadily but in spurts. The combination of many factors, such as technological change and new ideas, creates conditions for rapid progress followed by slower-paced periods of "firming up" of ideas. The past two decades have seen renewed worldwide interest and intensive research into shelf edge processes.

2. Eddy interactions with the continental margin

There are many possible energy sources for low-frequency eddy motions near the edge of the continental shelf. Petrie (1983) credits the interaction of transient wind-driven flows with shallow banks for anomalous currents on the outer Scotian Shelf, whereas Pingree (1979) attributes baroclinic eddies bordering the Celtic Sea to hydrodynamic instability of a shelf break front. However, on the western sides of ocean basins, a more likely source is strong western boundary currents. When this current flows along the shelf edge, as the Gulf Stream does in the U.S. South Atlantic Bight (SAB), the forcing is direct in terms of "frontal eddies", which form on the inshore edge of the current and extend into shallow water. On the other hand, when the current lies farther offshore, like the Gulf Stream north of Cape Hatteras, the forcing is indirect via large-scale meanders and "pinched-off" Warm-Core Rings (WCR, See Figure 1). These features, which contain vast stores of potential energy in their mass fields, are capable of radiating low-frequency waves, known as topographic Rossby waves, up the continental rise and slope to the shelf edge. The development of ideas about these two different modes of shelf edge forcing by offshore currents will now be traced.

The earliest accounts of eddy currents in the SAB come from ship's logs in the late 1500's (Brooks and Bane, 1981). However, the first quantitative measurements of the velocity and temperature structures in the surface layers of the Gulf Stream were made by Webster (1961), who characterized the meanders off Onslow Bay as skewed, wavelike oscillations with periods of 4 to 7 days. Webster's observations, which were made with a bathythermograph (for temperature) and set of towed electrodes known as a geomagnetic electrokinetograph or GEK (for current), have been considerably augmented by modern measurement devices such as moored current meters, the CTD (Conductivity, Temperature, Depth profiler), and radiation thermometers borne by satellite or aircraft. In synthesizing the results of extensive field programs off Florida and the Carolinas, Lee *et al.* (1981) and Bane *et al.* (1981) have described the circulation of "frontal eddies" that produce warm salty tongues of Gulf Stream water that "fold backwards" along the inshore edge of the stream to enclose a core of rich upwelled water. With cross-stream scales of 10 km, the eddies amplify as they propagate northward (at an average rate of 40 km/day) with maximum growth rates occurring just north of the "Charleston bump", a localized topographic irregularity that deflects the Gulf Stream seaward. Brooks and Bane (1981) have demonstrated that the eddy fluctuations are not correlated with wind or coastal sea level, which suggests that their energy comes from hydrodynamic instability of the Gulf Stream front. The observed energy transformations and recent model results indicate that the primary source is the potential energy of the stream (i.e., baroclinic instability) and that the loss of the stabilizing effect of the steep shelf edge topography causes the enhanced growth rates north of the Charleston bump (e.g., Dewar and Bane, 1985).

After leaving the continental margin at Cape Hatteras, the dominant instability mode of the more "jet-like" Gulf Stream shifts to larger-scale, lower-frequency meanders of the entire current. These meanders often amplify and "pinch-off" to form both cold- and warm-core (WCR) rings on the southern and northern sides of the Stream respectively (Figure 1). Warm-core rings were first observed by Jonathan Williams, the grandnephew of Benjamin Franklin, in 1790. In the thirties, Iselin (1936) made numerous hydrographic observations of isolated WCRs, but their formation from a growing meander was not observed until the fifties (Fuglister and Worthington, 1951). The influence of rings and meanders on the coastal waters of the Scotian Shelf was noted by McLellan *et al.* (1953), who pointed out that the the position of the narrow boundary separating shelf and slope waters varied "unsystematically" by as much as 250 km in the region south of Halifax. More recently, BIO scientists have described how tongues of Scotian Shelf water may be drawn offshore by WCRs that approach the shelf, and have calculated that such large-scale exchanges, at the observed rate of six per year, have a significant impact on the heat, salt and nutrient budgets for the shelf waters (Smith, 1978). In fact, in the context of a simple box model, Houghton *et al.* (1978) have shown that measured low-frequency fluxes at the Scotian Shelf break are capable of supporting the observed alongshore gradients in temperature and salinity as well as the biological requirements for nitrogen, the single most important nutrient for supporting primary production on the Shelf (Fournier *et al.*, 1977).

In the deeper layers, the clockwise circulation of the WCR interacts with the shoaling topography of the continental rise to generate topographic Rossby waves (TRW) which radiate energy away from the ring. The properties of linear, inviscid TRW were originally explored theoretically by Rhines (1970) and confirmed by a series of long-term current meter measurements on the New England continental rise described by Thompson (1977). Theories have also been developed for the transmission and reflection of TRW energy on the steep continental rise and slope (e.g., Kroll and Niiler, 1976) and for scattering some of that energy into trapped baroclinic waves ("fringe modes") at a sharp change in topography such as the shelf break (Ou and Beardsley, 1980).

Although these simple models presume that the energy source for the TRW is the Gulf Stream, direct evidence for a generation mechanism was not obtained until 1976-77 during an experiment conducted by BIO scientists at the shelf break south of Halifax. Important elements of the Shelf Break Experiment were an array of 11 moorings at 8 sites (Figure 2a) and a series of weekly sea surface frontal analyses based on satellite infrared imagery which were digitized on a 10 × 10 km grid oriented to the shelf break (Figure 2b). During July/October, 1976, near bottom records of alongshore current (Figure 3) revealed a burst of topographic wave energy in which the period gradually increased and the phase propagated offshore [consistent with onshore energy flux; Louis *et al.*, 1982]. Louis and Smith (1982) then formulated an initial value problem for an isolated circular vorticity disturbance on the Scotian Rise, which explained both the temporal variations in wave period (Figure 4a) and amplitude (Figure 4b). As a result, the generation time for this wave packet was identified as week 27, 1976, when the frontal analyses indicated that a WCR known as Eddy I was forming 200 km south of the array (Figure 5), and the scale of the vorticity disturbance beneath the ring was estimated to be 70 km. Furthermore, analysis of the three-dimensional TRW energy flux over realistic topography indicated that the strength of low-frequency current oscillations at the shelf break was determined by competition between amplifying effects of shoaling and refraction versus decay due to radial spreading of the energy. However, for reasonable estimates of bottom frictional dissipation, the wave energy that reaches the shelf edge is expected to decay over alongshore scales of 100 km, so that the disturbances caused by WCR are localized to that extent (Smith, 1983).

With regard to their influence on the shelf circulation, Garrett (1979) has shown that the strong TRW currents at the shelf break are capable of inducing upwelling via the bottom Ekman layer, a process which may contribute to the enhancement of cross-shelf fluxes at low frequencies. However, longshore wind is also effective at producing shelf-break upwelling at somewhat higher frequencies.

Further north, the Labrador Current flows southward along the edge of the Labrador/Newfoundland Shelf and the Grand Banks as part of the sub-polar gyre in the North Atlantic. Like the Gulf Stream in the South Atlantic Bight, the Labrador Current is co-located with the steepest portion of the continental slope and its meandering produces strong low-frequency variability in the current field. LeBlond (1982) has observed this variability at the surface using a frequency of visual images of the offshore ice margin on the Larador Shelf taken from a NOAA-5 satellite. He attributes the amplifying undulations, with characterisitic periods of 4 days and wavelengths of 75 km, to baroclinic instability of the Labrador Current frontal system. In the offshore region, Allen (1979) has found evidence in moored current meter measurements for topographic Rossby waves propagating shoreward in the deep waters of the continental rise. These fluctuations, at periods of 4 to 8 days, are similar to those found on the Scotian Rise and may be associated with eddy acivity in the Labrador Sea.

3. Wind-induced upwelling

On a broad continental shelf (i.e., much wider than the typical baroclinic adjustment scale of about 10 km), the response to longshore-wind forcing occurs both at the coast and in the vicinity of sharp changes in the bottom slope such as the shelf break. Since the early seventies many theoretical and experimental investigations have been focussed on the coastal upwelling phenomenon, most notably on the narrow shelves of the west coasts of North and South America where the shelf-edge and coastal responses are merged. However, theoretical and particularly observational studies of wind-induced shelf-break upwelling are sorely lacking (Huthnance, 1981).

Using a simple two-dimensional "step-shelf" model, Huthnance (1981) demonstrated that shelf-break upwelling is caused by a divergence of the offshore flow in the surface layer which is proportional to the large depth change between the shelf and ocean as well as the strength of the forcing. With a similar two-layer model, Csanady (1973) showed that the character of a wind-induced longshore jet at the shelf break was controlled by the distribution of bottom slope and stratification. Janowitz and Pietrafesa (1980) have also formulated a model for transient upwelling, which includes both bottom friction and weak stratification. Their results suggest that sufficiently sharp changes in the bottom slope at the shelf break produce a persistent upward bulge in the isopycnals, which implies a vertical shear in the longshore current according to geostrophic dynamics. Furthermore the strength and timing of this model circulation are in reasonable agreement with measurements in the SAB, where wind-induced upwelling in summer is credited with supplying significant quantities of nutrients to the mid-shelf region (Atkinson *et al.*, 1982).

On the Scotian Shelf, early hydrographic observations (e.g., McLellan *et al.*, 1953; Hachey, 1953) indicated that the Scotian Gulf, which lies between Emerald and LaHave Banks south of Halifax, is a favoured location for wind-driven slope water intrusions. Petrie and Smith (1977) suggested that such events are capable of flushing the deep waters of Emerald Basin in the fall and winter. More recently, Petrie (1983) has found evidence in data from the BIO Shelf Break Experiment (Figure 2) that moderate (10-20 m/s) longshore winds that persist for at least two days produce upwelling at the shelf break from depths of 400 m or more on the continental slope. Peak vertical velocities are of order 2 mm/s and the upwelling appears to be confined to within 10 km of the slope. Furthermore, the vertical longshore current shear and horizontal density gradients at the shelf break were found to be in geostrophic balance. However, on the shelf, large anomalous bottom currents with maxima near 1 m/s (Figure 6) were attributed to local topographic variations on the outer banks. Moreover, attempts to model the transient current fields with two-dimensional analytical and numerical models failed both quantitatively and qualitatively! Thus, in the presence of complex topography, the wind-driven response at the shelf break is essentially three-dimensional.

The Labrador and Newfoundland shelves also have complex topography characterized by numerous banks and saddles. Hence in these regions also, shelf-break upwelling is expected to be a fully three-dimensional phenomenon. However, an additional complication is introduced by the presence of the Labrador Current front which serves to enhance cross-shore exchange induced by upwelling-favourable winds (Ikeda, 1985).

4. Internal tide and nonlinear waves

One question that arises with regard to the low-frequency shoreward fluxes of nutrients, which are concentrated from mid-depths to the bottom at the shelf break, is: How do they reach the euphotic zone at the surface? One likely mechanism is vertical mixing caused by internal waves.

The discovery of internal waves dates back to the early part of this century. The rapid development then, which included the development of many new instruments (e.g., the Ekman current meter) and techniques, was led by Scandinavian oceanographers stimulated by the need to know more about large fluctuations in the food supply for fish. Nansen (1902) was the first to observe internal waves in the ocean, but it took Ekman's (1904) model calculations to identify them. Many more observations of internal waves followed, and Fjeldstad (1933) extended the dynamical theory from the early layered models to a continuously stratified fluid.

By 1960, despite a large volume of literature or internal waves, little was known about their generation and distribution in the ocean. But then Rattray (1960) used a simple two-layer, step-shelf model to demonstrate coupling between the surface and internal tides. In 1962, Cox and Sandström calculated the rate of energy flow from surface to internal tides by scattering from bottom roughness in a continuously stratified ocean. This paper has since become a cornerstone in the study of deep ocean internal tides. The early sixties also saw the first applications of optical ray theory to oceanographic problems (e. g., Sandström, 1966). This technique has formed the basis for many important subsequent investigations of the interaction between surface and internal tides - for example by Baines, (1974) and by Prinsenberg and Rattray (1975). According to Baines' model, the most efficient conversion of energy occurs where the local topographic slope and the ray slope of the internal tide are equal. This condition is generally met at the shelf edge.

At BIO, internal tide studies of the seventies were aided by both theoretical advances and new instrumentation of the sixties. Thus both Warner (1970) and Petrie (1975) analyzed moored current and temperature measurements on the Scotian Shelf and Slope. Petrie, in particular, demonstrated that the intersections of critical rays from generation sites at the shelf break with the moorings were consistent with the observed structure of the M_2 internal tide (Figure 7). In addition, Sandström (1976) formulated a unified ray theory to explore the sensitivity of the topographic generation problem to variations in stratification and bottom profile. In the St. Lawrence estuary Forrester's (1973) examination of hydrographic variability clarified the role of internal tides generated at the head of the Laurentian Channel.

In this decade, internal tide research has been spurred first by the realization that internal tides cause or enhance fine and microstructure events related to ocean mixing and second by the discovery of finite-amplitude, short internal waves (solitons, internal bores), which are somehow related to the internal tide. Groups of these short-period (e.g., 10 min) waves have been detected at certain phases of the M_2 tide in many locations, usually with temperature measurements [e.g., in the Strait of Gibraltar by Ziegenbein (1969), in Massachusetts Bay by Haury *et al.* (1979), in British Columbia fjords by Farmer and Smith (1980) and, more recently, on the shelves of northern Europe by Pingree and Mardell (1985), who emphasize their biological importance]. These studies have benefitted considerably from the development of remote sensing techniques to study the ocean from satellite-, aircraft- and shipboard platforms.

In 1980, BIO scientists commenced a multi-year investigation of the relationships between tides, turbulence, and ocean mixing at the edge of the Scotian Shelf, in order to understand the reasons for high nutrient concentrations and biological productivity in the euphotic zone. Furthermore, observations have been made all along the Scotian Shelf and Grand Banks of Newfoundland to map the occurrence and nature of the large amplitude waves, and this information has been provided to offshore industry concerned with their potentially-harmful effects (e.g., current surges). In conjunction with the field program, theoretical studies of the connection between the internal tide and ocean mixing are continuing. Much of the recent progress in this work is due to BATFISH, a towed undulating body developed at BIO (Dessureault, 1976) for surveying hydrographic properties in the surface layer (Figure 8). Acoustic sounding systems using single or multiple frequencies have also been used to provide high resolution images of short internal waves at the shelf break (Figure 9), while rapid sampling turbulence probes (Oakey, 1983) serve to quantify ocean microstructure and dissipation rates.

Packets of short internal waves have also been detected as far north as Davis Strait (Cummins and LeBlond, 1981) indicating that they are a ubiquitous feature of the continental shelf break circulation in the western North Atlantic.

5. Conclusion

In summation, progress in understanding three distinctive physical processes at the shelf break has been described. The low-frequency forcing of the shelf break circulation by strong western boundary currents and mesoscale eddies in the U.S. South Atlantic Bight, where the Gulf Stream itself meanders onto the shelf, and on the Labrador/Newfoundland Shelf, where the Labrador Current flows along the shelf break, has been contrasted to the situation on the Scotian Shelf, where intermediary Warm Core Rings radiate low-frequency topographic Rossby waves to the shelf break and promote mixing across the shelf/slope water boundary. Wind-induced upwelling at the edge of the Scotian Shelf has also been shown to result in exceptionally strong bottom currents as a result of the complex topography on the outer banks while the presence of the Labrador Current front at the shelf break promotes cross-shelf mixing induced by wind. And finally, advances in our knowledge of the internal tide and large-amplitude internal waves at the shelf break promise to lead to a clearer understanding of oceanic mixing as it relates to biological productivity on the continental shelf.

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1. A satellite infrared image showing the interaction between a warm-core Gulf Stream ring (dark) and colder surface shelf water (light).

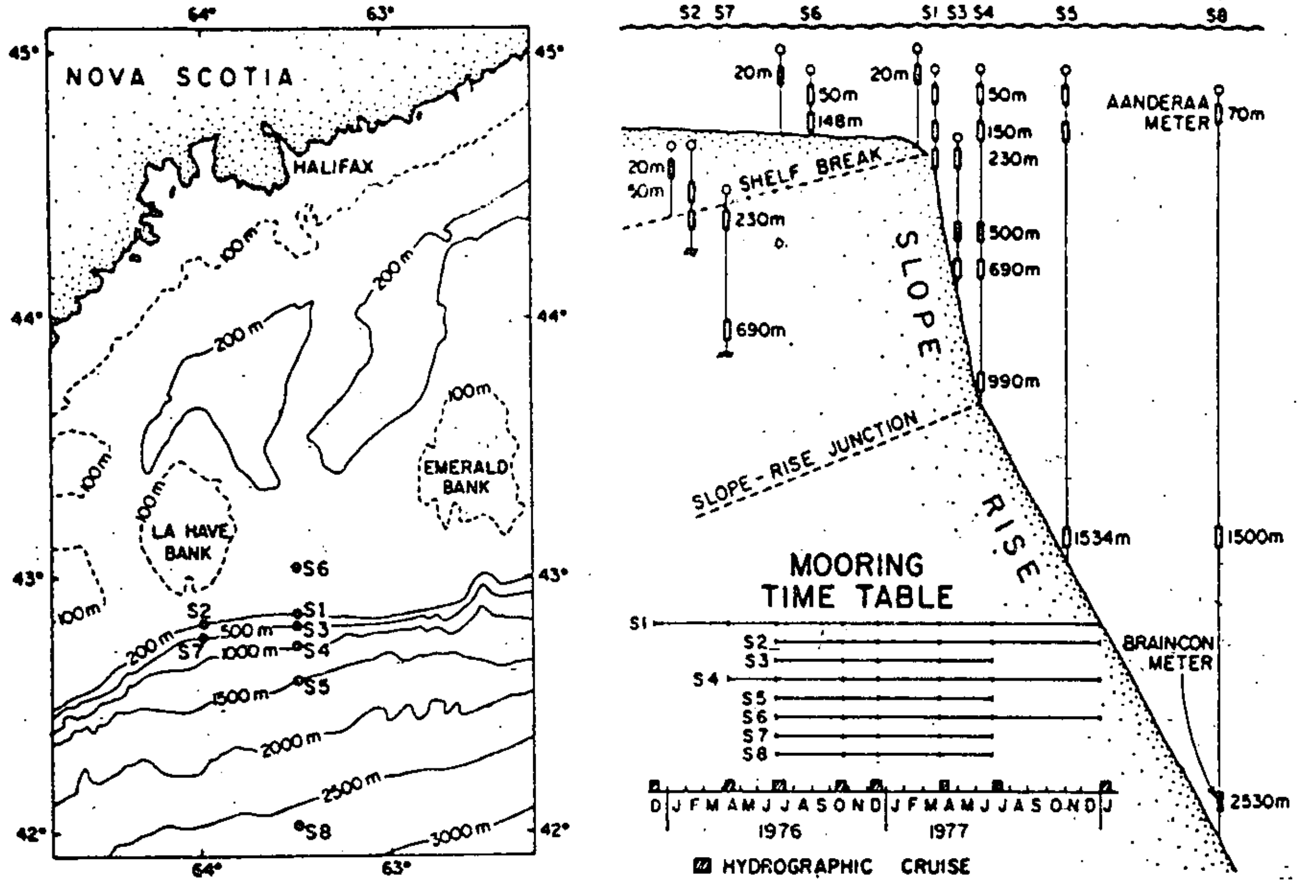


Fig. 2a

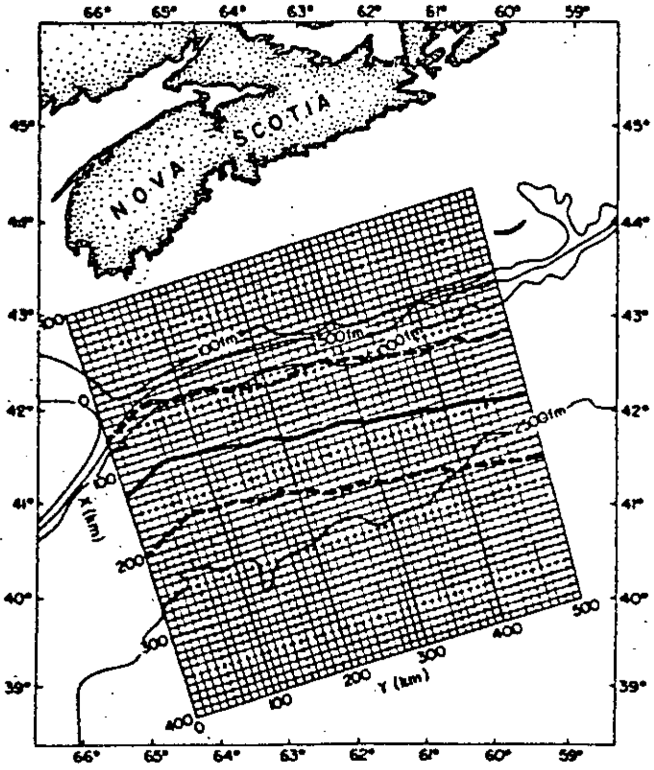
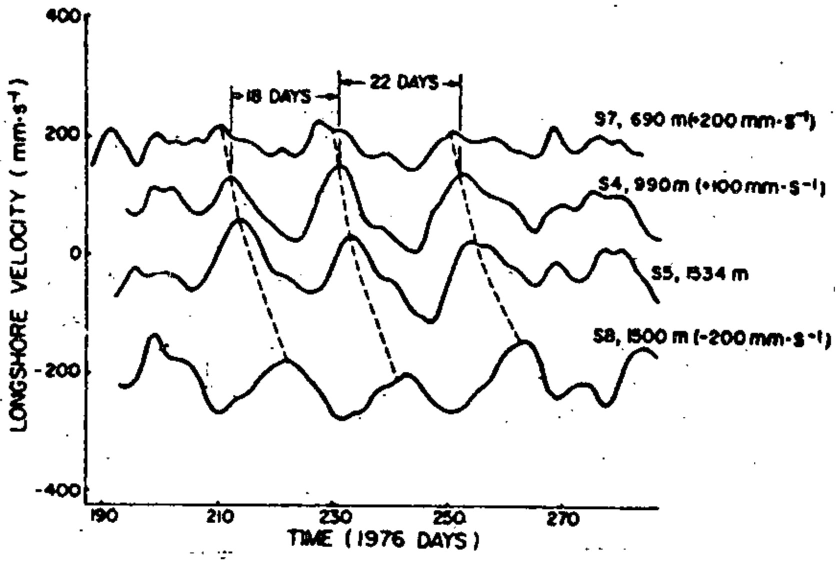
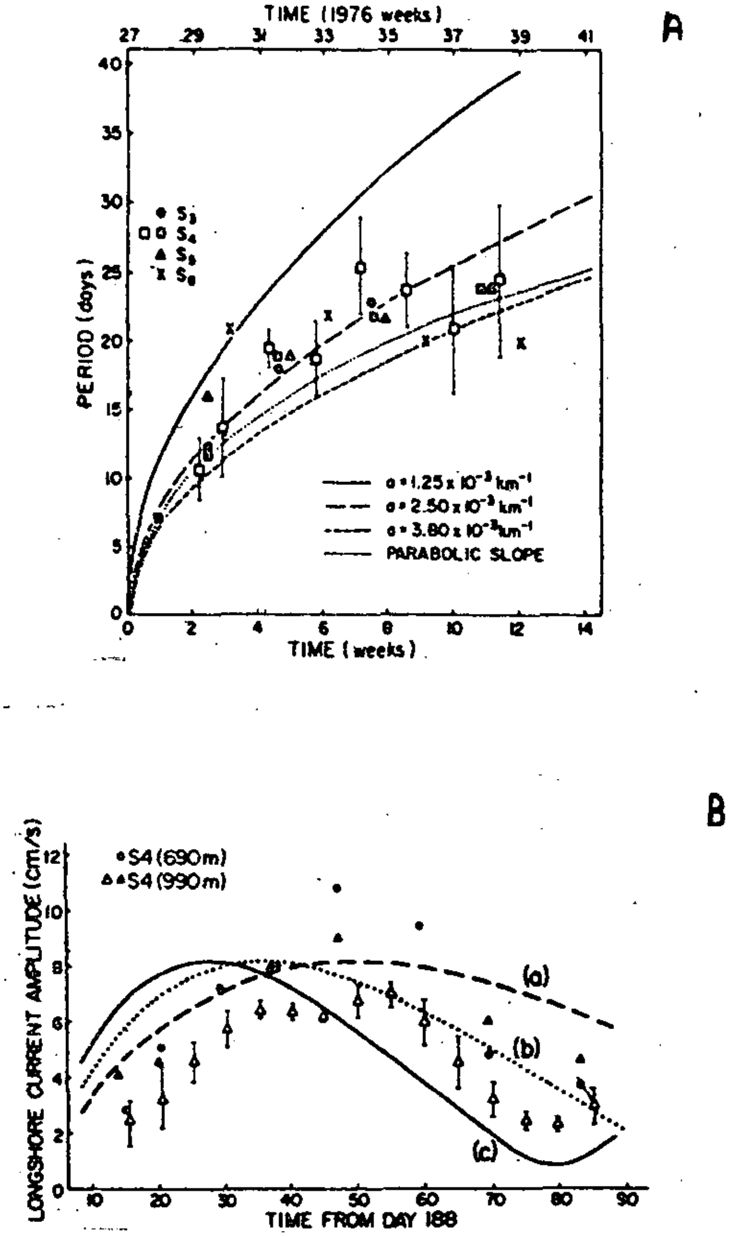


Fig. 2b

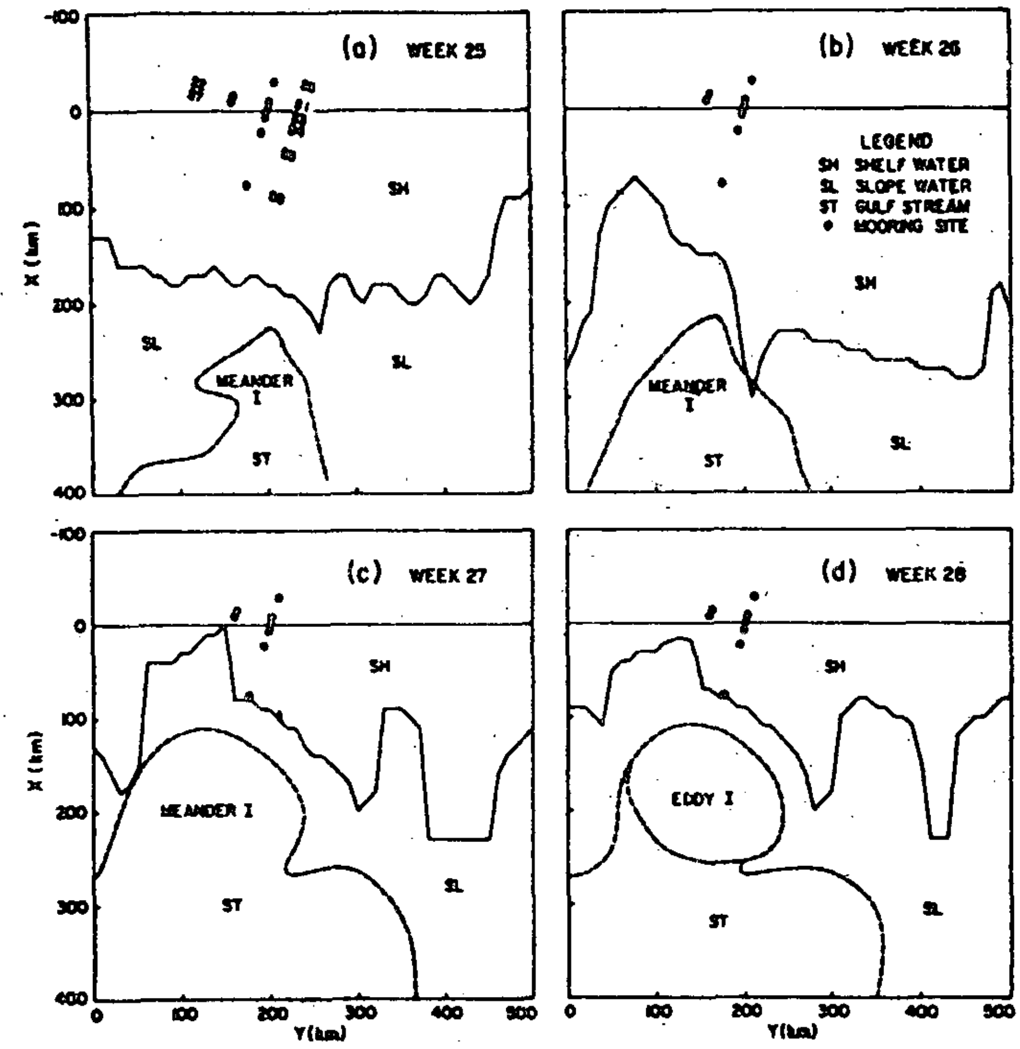
2. The monitoring networks for the BIO Shelf Break Experiment: December 1975 to January 1978. a) Mooring array and time table. b) 10 × 10 km grid used to digitize the position of the shelf/slope water boundary and Warm Core Rings. Mean position (solid) and standard deviation (dashed) of the shelf/slope water boundary are shown for the period of the experiment.



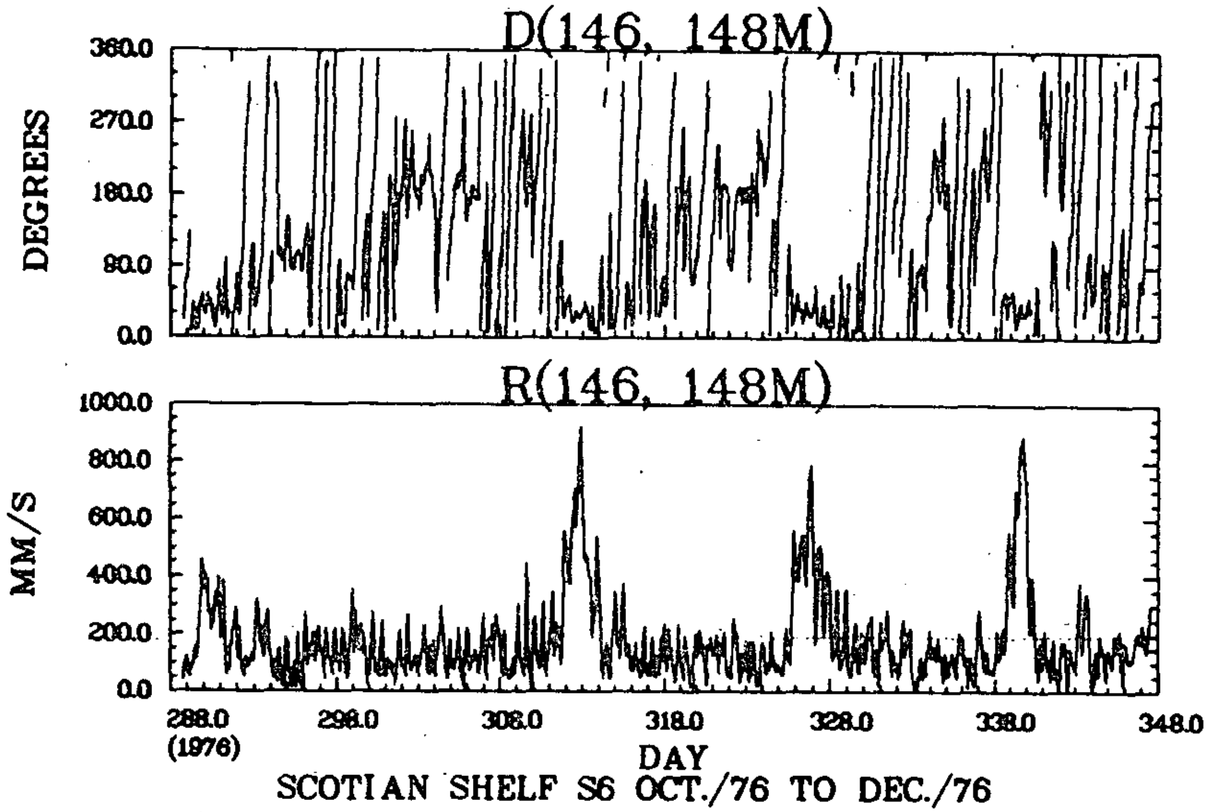
3. **Filtered records of the longshore (eastward) current at deep instruments in the offshore region during July/October, 1976. Dashed lines indicate offshore phase propagation; period variations are shown for the S4 record.**



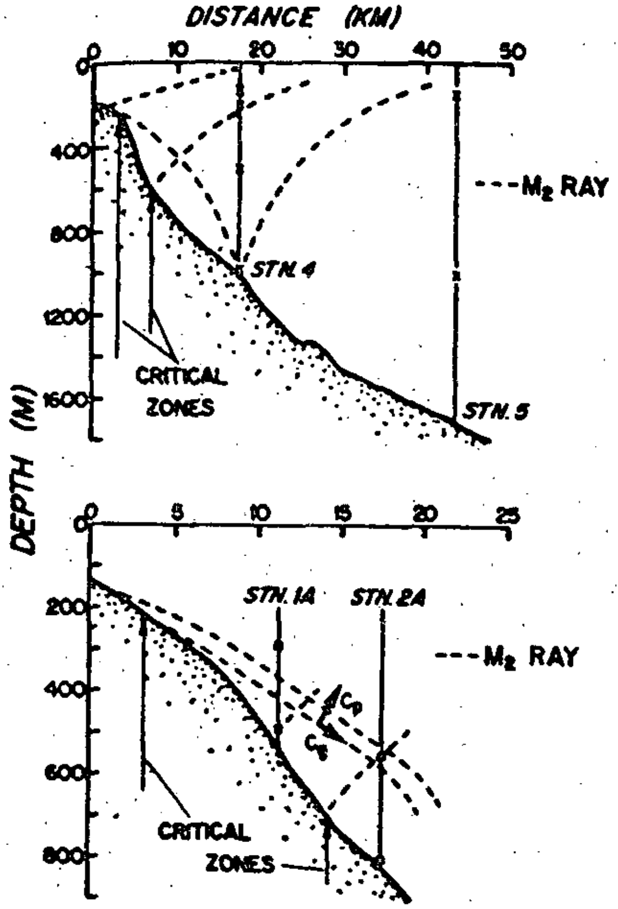
4. a) The observed (symbols) and model (curves) wave period versus time for topographic wave oscillations 200 km north of the initial disturbance. Curves represent various definitions of model topography. b) The observed (symbols) and model (curves) wave amplitude variations at the S4 mooring site. Best model fit is achieved for an initial disturbance with a diameter of 70 km (dotted curve).



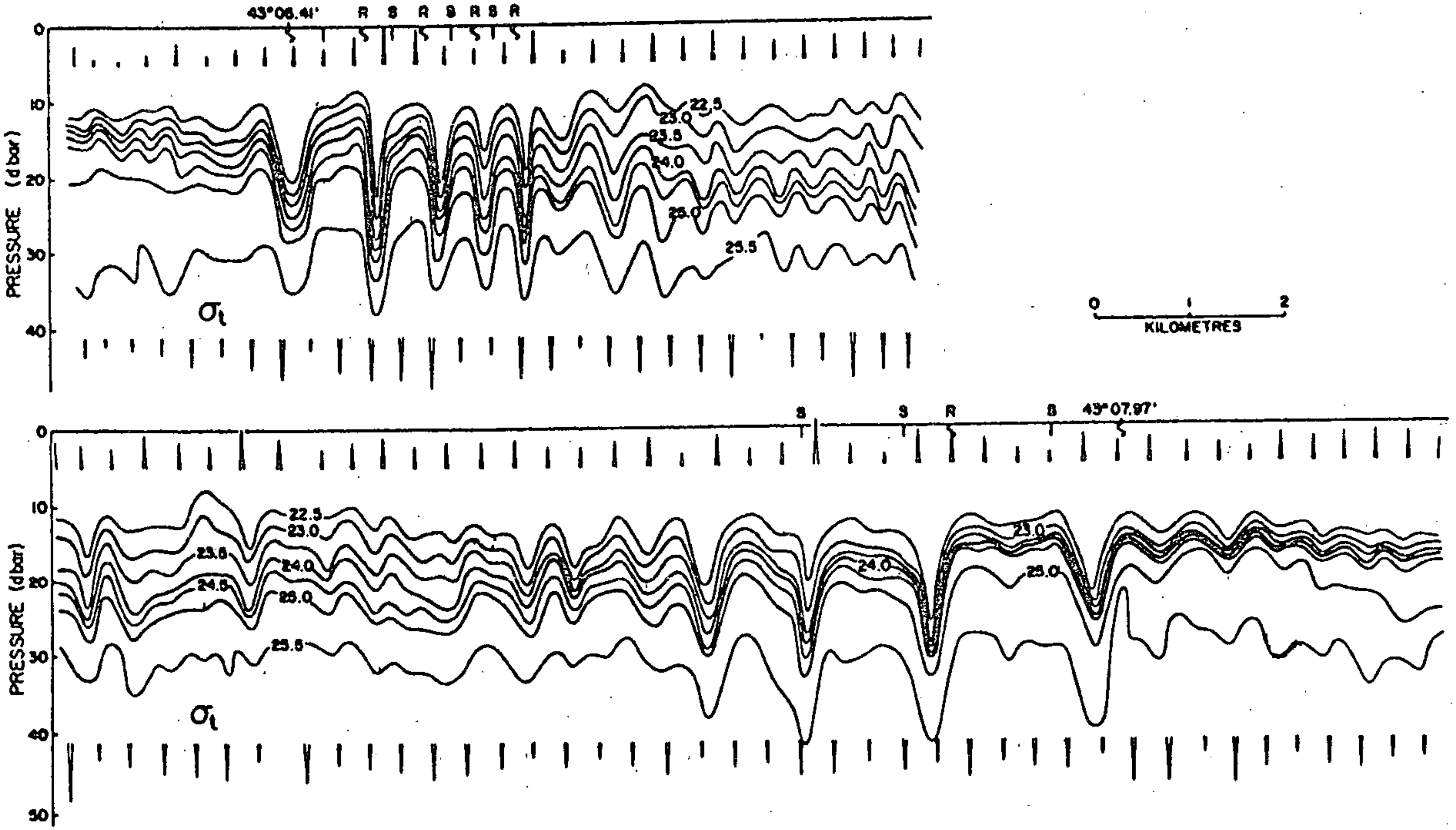
5. a-d) Frontal analysis of sea surface temperature depicting shelf/slope water boundary (solid) and north wall of the Gulf Stream (dashed) on a rectangular grid with one axis roughly coincident with the shelf break (Figure 2b). Panels a) to d) illustrate the formation and development of Eddy I during weeks 25 to 28 of 1976.



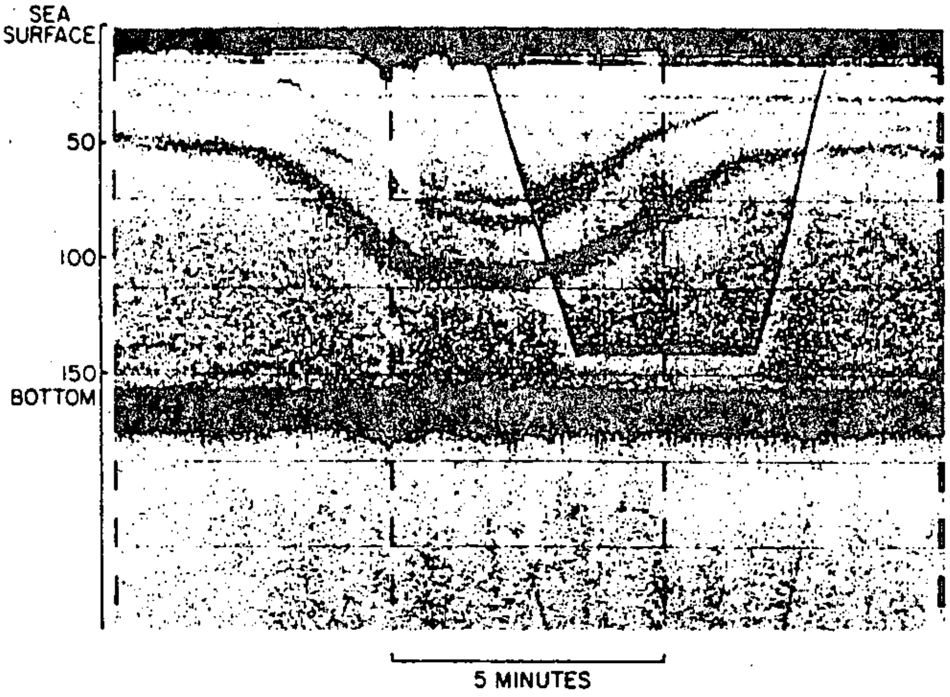
6. A time series of rate and direction from the shelf mooring, S6, at 148 m during October through December 1976.



7. Topographic profiles on the Scotian Slope with positions of current meter moorings. Dashed curves indicate critical rays for the M2 internal tide, which intercept the slope near 200 and 600 m (from Petrie, 1975).



8. The density field observed by BATFISH for two consecutive crossings of a short internal wave packet: top-ship and waves travelling in opposite directions; bottom-ship overtaking the waves. A banded pattern observed at the surface is marked as R = rough and S = smooth.



9. An internal soliton on the shelf as seen by the 12-kHz sounder. The "bucket" is the trace of CTD package traversing the water column.