Current Variability over the Scotian Slope in the 1990s

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Abstract. TOPEX/POSEIDON sea level data from mid 1992 to early 2000 are analysed to investigate sea-surface current variability over the Scotian Slope off Atlantic Canada. One–second sea level data are de-spiked and smoothed in the along-track direction, and sea level anomalies relative to local means for this period are calculated. Geostrophic surface current anomalies normal to ground tracks are then derived from the sea level anomalies. Climatological-mean surface currents normal to the ground tracks are also obtained from the solutions of a regional finite-element circulation model. Model means and altimetric current anomalies are superimposed to produce nominal absolute currents. The altimetric results reveal prominent current variability over the Scotian Slope, intensifying toward the west and south. The intensification seems to be associated with the high occurrence of Gulf Stream rings and the proximity to the Gulf Stream. The rotational speed of the rings can exceed 1 m/s. The cyclonic slope circulation is stronger in winter/fall and weaker in summer/spring. The present analysis also indicates that the winter circulation was strongest in 1998 and weakest in 1996. The altimetric currents are consistent with frontal analysis data, ADCP and CTD observations, and numerical model results.

Keywords. Current variability, Gulf Stream rings, satellite altimetry, Scotian Slope

1 Introduction

The Scotian Slope (Fig. 1) and Rise off Nova Scotia is generally considered to be a region of strong current variability (Smith and Petrie 1982; Csanady and Hamilton 1988). The mean circulation is believed to be a broad cyclonic gyre in the Slope Water, between the northeastward Gulf Stream carrying warm and saline water and the equatorward shelf-edge current mainly composed of the colder and fresher Labrador Current water and the Gulf of St. Lawrence outflow water. Meanders and anticyclonic warm rings pinched off from the Gulf Stream often modify the Slope Water circulation. These rings generate significant temporal and spatial variability in currents (Joyce, 1991) and provide an important mechanism for shelf/deep-ocean exchange processes. It has been shown that the Labrador Current transport and the Gulf Stream position experienced significant interannual changes in the past decade (Han, 2002).

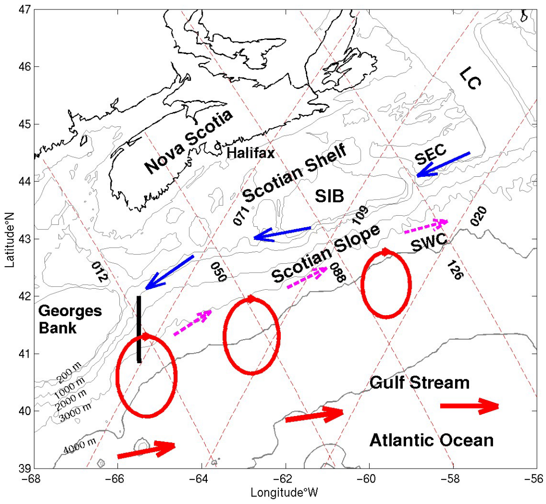

Fig. 1 Map showing the Scotian Slope, and adjacent shelf and deep oceans. The labeled dashed lines are the selected T/P ground tracks on which the analysis is performed. The thick solid segment indicates the location of a hydrographic survey section. SEC: Shelf-edge current; SWC: Slope Water current. LC: Laurentian Channel. SIB: Sable Island Bank. Gulf Stream rings are depicted in red ellipses.

Studies of Slope Water circulation including both observational programs and theoretical studies have been limited, compared with those of the Gulf Stream and the shelf areas. Therefore, our present quantitative knowledge about the circulation in the

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Slope Water region is limited, particularly over the Scotian Slope. Recent mooring observations together with drifter studies (Fratantoni, 2001) have started a new phase of observing the Slope Water currents variability. Satellite altimetry provides instantaneous sea surface height measurements relative to a reference surface, and has been used to study the Gulf Stream and the shelf edge currents (e.g. Han, 1995). Earlier exploratory studies also indicate T/P altimetry's potential in complementing in situ measurements for quantifying current variability and understanding dynamics in the Slope Water region (Han et al., 2000; Han, 2002).

The primary purpose of this study is to use TOPEX/POSEIDON (T/P) satellite altimeter data for estimating surface current statistics for the Scotian Slope. In conjunction with frontal analysis data and other hydrographic data, this manuscript describes and discusses major current features. Knowledge of currents and their variability will be particularly important for oil and gas activities in the deep waters of the Scotian Slope. The altimetric current information is highly valuable for better understanding slope circulation dynamics and constraining dynamic circulation models.

In section 2, we describe T/P data and processing techniques, derivation of surface currents, and frontal analysis data. Section 3 presents sea level and currents features and statistics at various temporal and spatial scales. Comparisons of altimetric results with other observations and model solutions are made in Section 4. Section 5 provides a brief summary and discussion.

2 Methodology

2.1 T/P Altimeter Data

We used corrected T/P sea-surface height data for the period from mid 1992 to early 2000, obtained from NASA Pathfinder Project. Three T/P ascending tracks and four descending tracks were selected across the Scotian Slope and Rise off Nova Scotia (Fig. 1). The satellite has a nominal repeat cycle of 10 days, and there are 276 observations at each location. The along-track resolution is about 6 km. The data were corrected based primarily on the principles in Benada (1997) for various atmospheric and oceanographic effects.

The standard NASA Goddard Space Flight Center precise orbit based on the Joint Gravity Model-3 (JGM-3) has been used to produce the sea surface height data relative to a reference ellipsoid with equatorial radius of 6378.1363 km and a flattening coefficient of 1/298.257.

Occasional spikes in the sea-surface height data were removed by an along-track 3-point median filter, and an along-track digital filter with an approximate e-folding scale of 18 km was performed to reduce noise influences on the current estimates. The results presented will be based on the smoothed height data unless indicated otherwise. A mean sea surface was constructed from the available T/P data. We then calculated the sea surface height anomalies relative to the mean sea surface. Both the marine geoid and mean oceanic topography are removed by this procedure. The sea surface height anomalies for Track 071 on October 20, 1999 are shown in Fig. 2, which exhibit prominent along-track variations in the Slope Water region (39-42^{o}N).

2.2 Derivation of Surface Current Anomalies

From the T/P sea surface height anomalies, geostrophic surface currents normal to the track (Fig. 2, positive westward) were derived. Note that these are estimates of surface current anomalies normal to the satellite ground tracks about the mean only, associated with the along-track pressure gradient derived from the slope of sea surface (e.g. local wind-driven flows are not included).

2.3 Calculation of Absolute Surface Currents

An approximate way of constructing absolute surface currents is to combine altimetric surface current anomalies with the mean circulation field from numerical ocean models. In this study we have used climatological-mean circulation currents from Han et al.'s (1997) diagnostic finite-element model solutions. The model surface currents are interpolated onto the satellite ground tracks. The components normal to the track were then derived (Fig. 3). We can see a westward flow along the shelf edge and the upper continental slope and a eastward current along the lower continental slope. It's likely that these model currents underestimate the mean flows offshore of the upper slope since the model used false bottom topography offshore of the 1000-m isobath.

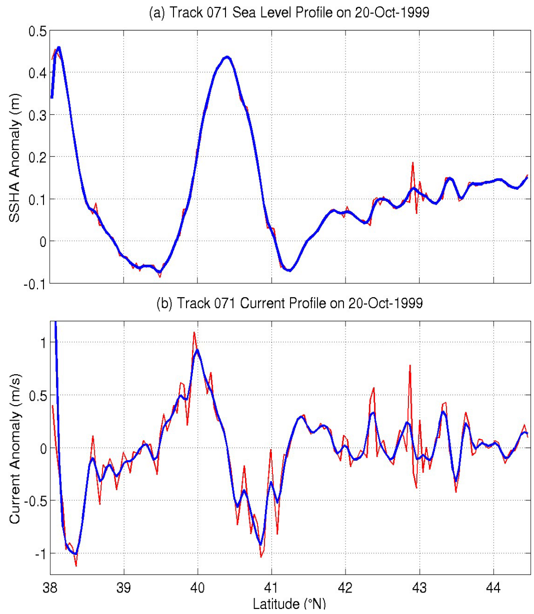


Fig. 2 (a) Along-track profiles of T/P sea surface height anomalies for Track 071 on October 20 1999, unsmoothed (red lines) vs. smoothed with the digital filter (blue lines). (b) Associated geostrophic current anomalies normal to the track.

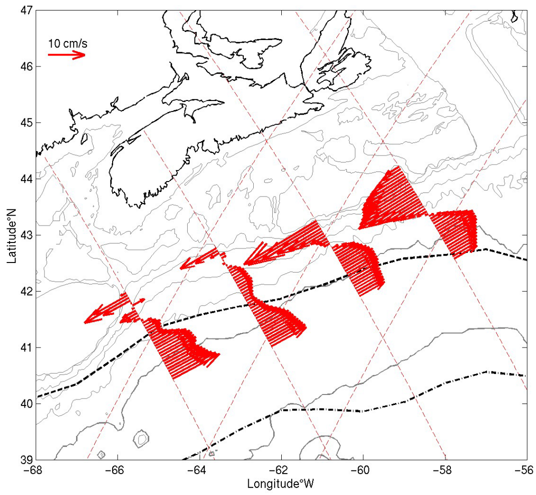


Fig. 3 Climatological seasonal-mean surface currents over the Scotian Slope derived from Han et al.'s (1997) model results. Also depicted are positions (thick dashed lines) of the shelf/slope front and the Gulf Stream northern wall (dash-dotted line) for the study period (see the next subsection).

2.4 Frontal Analysis Data

Frontal analysis data provide quantitative information on the location of surface temperature fronts (shelf/slope front, Gulf Stream rings and Gulf Stream) based on satellite imagery. Frontal positions have been digitized from "Oceanographic Features Analysis" charts published by NOAA up to the end of September 1995 (Drinkwater K. and R. Pettipas, personal communication, 2001). Starting in April 1996, the charts have been referred to as "Jennifer Clark's Gulf Stream" (for more information visit http://users.erols.com/gulfstrm/).

Fig. 4 shows the shelf/slope front (the narrow boundary separating cool shelf water from the warmer slope water immediately offshore), the Gulf Stream northern boundary separating the Stream from the slope waters, and warm temperature patches with some of them associated with Gulf Stream warm core rings (WCR), on October 20, 1999. A Gulf Stream ring is apparent over the continental slope off Georges Bank and the western Scotian Shelf (between 39.5 and 41^{o}N).

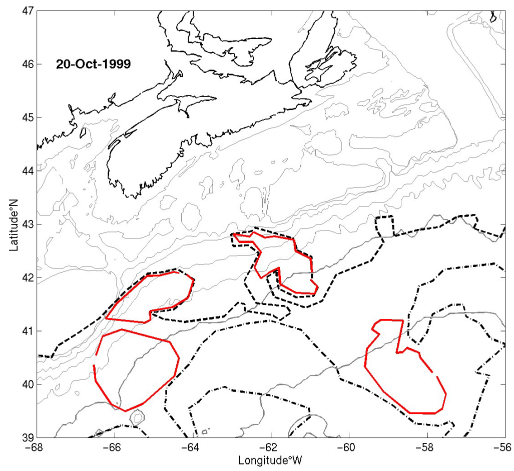


Fig. 4 The positions of the shelf/slope front (dashed line) and the Gulf Stream northern wall (dash-dotted line) and the warm temperature patches of surface water (red) derived from satellite thermal imagery on October 20, 1999.

3 Results

The sea surface height anomalies on Track 071 (Fig. 2a) show large along-track variations in the Slope Water region (39-42^{o}N), associated with fluctuations in the Gulf Stream position and the occurrence of WCRs (see Fig. 4). The associated current anomalies (normal component) have magnitudes of order 1 m/s (Fig. 2b). Anticyclonic ring circulation apparently occurred on October 20, 1999 between 39.5 and 41.5^{o}N, indicated by the negative (eastward) current anomalies around 41°N.

There are significant interannual variations in the current anomalies, as seen in time series of the anomalies near the 1000- and 4000-m isobaths on the descending tracks that are approximately normal to the shelf edge (Fig. 5a) and their power spectra (Fig. 5b). The seasonal and intra-seasonal changes are also apparent. For Tracks 12 and 50 the currents variability at the 4000-m water depth is much larger than that at 1000-m depth, while differences for Tracks 88 and 126 are not evident. This is consistent with the increasing distance of the Gulf Stream from the continental slope as one proceeds eastward from Georges Bank towards Grand Bank.

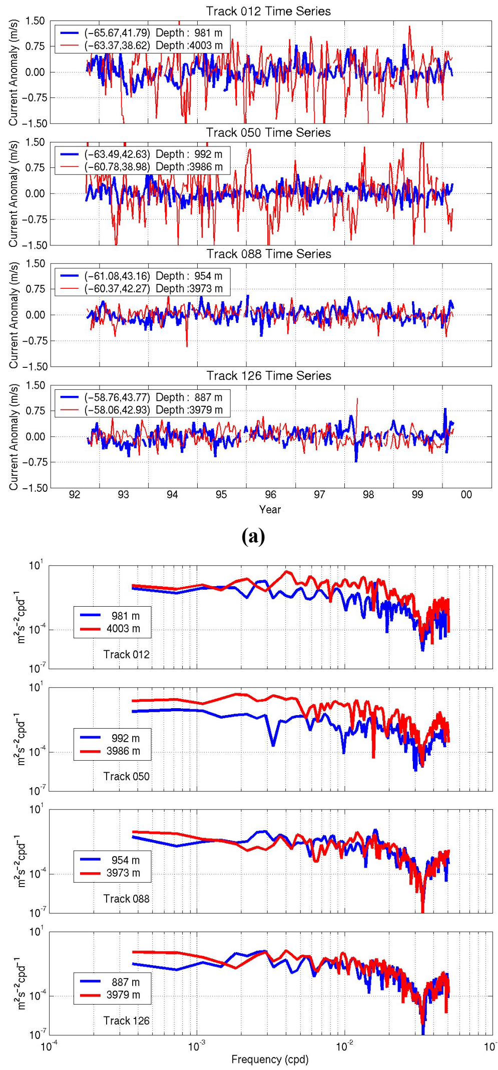


Fig. 5 Current anomalies at nominal 1000-m and 4000-m water depths on the four descending tracks (a) Time series, and (b) Power density.

Fig. 6 shows the spatial distribution of root-mean-square (rms) variability of the cross-track currents on the 7 tracks. Over the Scotian Slope, the variability increases westward and offshore, especially in the western part. This westward intensification can be attributed to proximity of the Gulf Stream to the shelf edge and increased warm core ring activity to the west (Fig. 7). The percentage occurrence of WCRs for a selected area is computed as the ratio of the number of days when a ring's average radius is 90 km or larger and its average center is located inside the area, to the number of total days. We also calculated the percentage occurrence with average radii of > 60 and 120 km respectively and found that the relative occurrence among the four areas is insensitive to the choice of the radius.

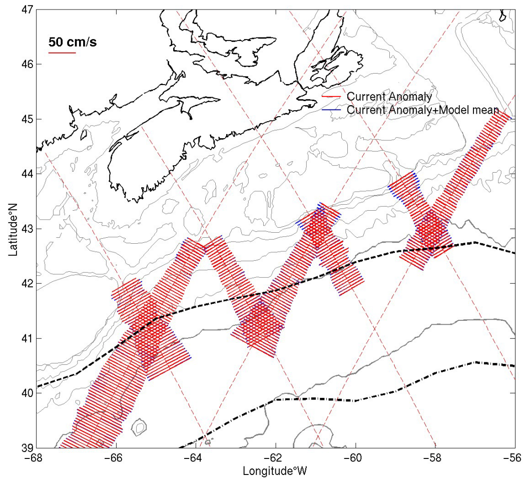


Fig. 6 Variability of the altimetric current anomalies from 1992 to 2000 plotted as twice the rms values (red). The blue segments show the differences of rms values when Han et al.'s model means are included. Positions of the shelf/slope front and the Gulf Stream northern wall are depicted as in Fig. 3.

The inclusion of the model mean currents does not change the rms values significantly (especially over the lower slope) (Fig. 6), indicating the eddy kinetic energy is overwhelmingly dominant over the mean kinetic energy for the Scotian Slope surface circulation. Nevertheless, it's likely that inclusion of a refined model mean with a more realistic representation of the Gulf Stream and associated currents would result in quantitative changes in the current statistics, particularly offshore of the 1000-m isobath.

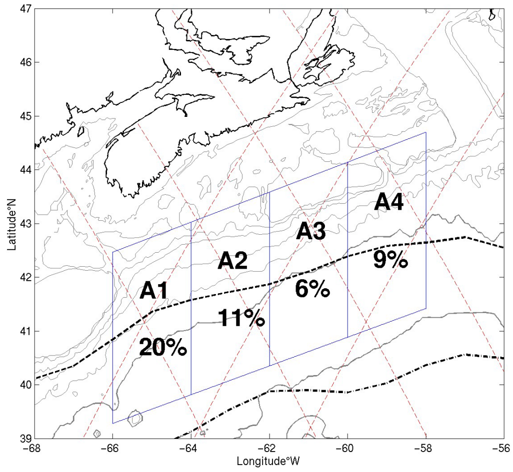


Fig. 7 Percentage occurrence of WCRs over the Scotian Slope based on the frontal analysis data (K. Drinkwater and R. Pettipas, personal communication, 2001) from 1992 to 2000. Positions of the shelf/slope front and the Gulf Stream northern wall are depicted as in Fig. 3.

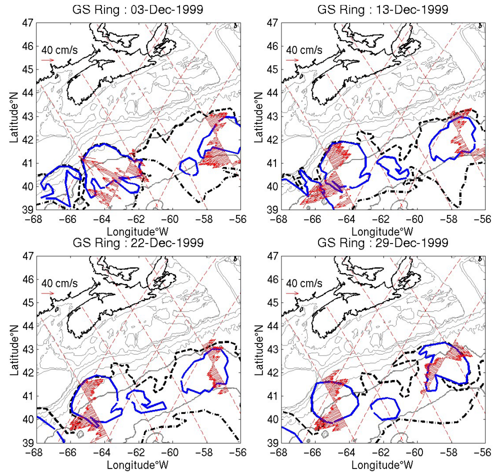
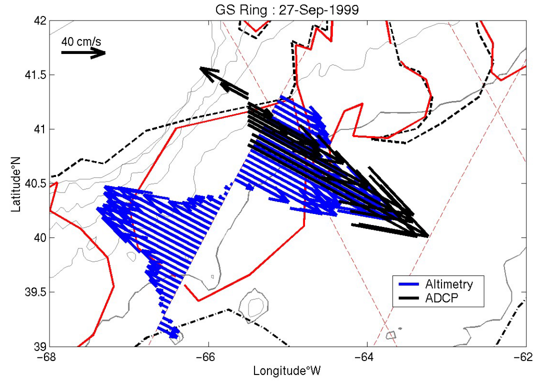


Fig. 8 Selected frontal analysis data (in blue for ring features, in dashed line for the positions of the shelf/slope front, and in dash-dotted line for the Gulf Stream northern wall) and altimetric current anomalies at the nearest repeat cycles (arrows).

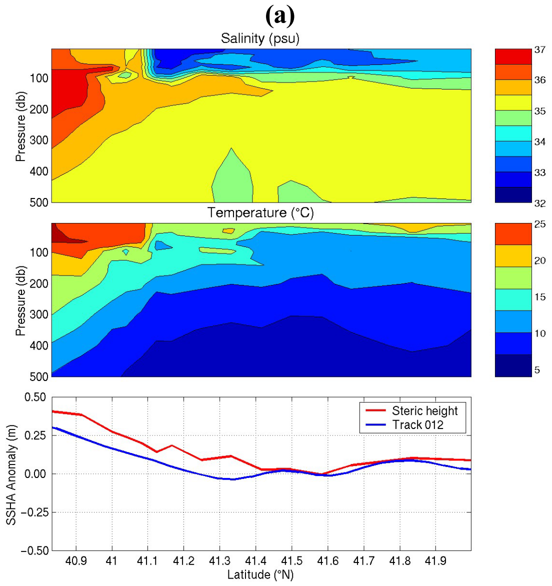
Altimetric data indicate anti-cyclonic eddies from time to time. These circulation features are apparently associated with warm patches revealed from infrared images. When there were WCRs from frontal analysis data, altimetric data also shows anticyclonic eddies in the same location (Fig. 8). The geostrophic currents associated with these eddies can be over 1 m/s. These eddies slowly drift westward and move inshore. They can last a few months and are usually reabsorbed into the Gulf Stream or may break apart if they move onto the Scotian Shelf. Altimetric data not only confirm the occurrence of the Gulf Stream rings revealed from the infrared images, but also provide important quantitative information about associated currents.

On September 27 and 28, 1999, ADCP and CTD data were collected at a section across a Gulf Stream/WCR front on 65 30’ W off the southwest Nova Scotia (Smith et al., 1999). The near surface currents from ADCP (Acoustic Doppler Current Profiler) data were presented in Fig. 9a. We can see approximate agreement of the eastward current on the northern side of the ring. Fig. 9b shows the temperature and salinity distribution from CTD (Conductivity-Temperature-Depth) data, which clearly shows that the temperature is above 18^{o} and the salinity is 3 unit higher of WCR water. The steric height calculated from the temperature and salinity data relative to the 500db is consistent with the altimetric sea level anomalies on Track 12 (Note that they are translated to be equal at the intersection).

Altimetric seasonal-mean current anomalies (Jan-Mar, Apr-Jun, Jul-Sep, and Oct-Dec for winter, spring, summer and fall respectively) averaged over all years were calculated from the T/P current anomaly data. Long-term seasonal-mean current fields (Fig. 10) were then constructed by adding the model mean flows (Han et al., 1997) to the altimetric seasonal-mean anomalies. The southwestward shelf edge current is stronger in winter and weaker in summer. The seasonal range amounts to 10-20 cm/s. The eastward slope current (with the mean current toward the northeast (Fig. 3)) over the lower continental slope along the 4000-m isobath seems stronger in winter/fall, except for track 050 in winter. The rms current magnitude of the long-term seasonal means is 12.2, 8.0, 8.0 and 10.8 cm/s for winter, spring, summer and fall, respectively.



(a)



(b)

Fig. 9 (a) Altimetric current anomalies (red arrows) on Track 071, Gulf Stream rings (red), and ADCP data (black arrows). Plotted are the ADCP current components normal to Track 71. (b) CTD Temperature distribution across the ADCP section. See Fig.1 for location.

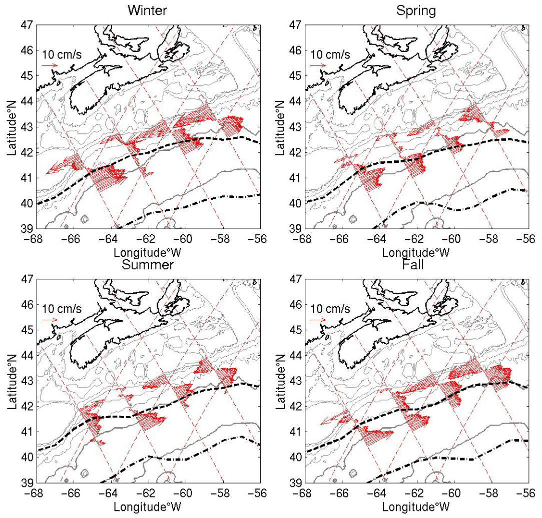


Fig. 10 Seasonal-mean currents over the Scotian Slope in winter, spring, summer and fall: altimetric seasonal-mean anomalies plus Han et al.' (1997) model means. Also depicted are positions (thick dashed lines) of the shelf/slope front and the Gulf Stream northern wall for each season.

We have also examined interannual variability of Slope Water circulation. The winter current fields (Fig. 11) indicate pronounced interannual changes. The slope circulation was weakest in 1996 (the northeastward branch disappeared completely!) and strongest in 1998 (up to 30-40 cm/s). The Gulf Stream was in its most northern position from 199 Scotain Shelf in 1997-98 (Han, 2002).3 to 1995 and shifted to the most southern position in 1996 (K. Drinkwater and R. Pettipas,personal communication, 2001).It is believed that the Labrador Current water pulse passed by along the upper Scotian Slope and intruded onto the the Scotain Shelf in 1997-98 (Han, 2002).

4 Summary and Discussion

We have used T/P altimeter data for the period from 1992 to 2000 to study sea surface current variability over the Scotian Slope. In conjunction with frontal analysis data and hydrodynamic model solutions, T/P data reveal significant current variability over the Slope at intra-seasonal, seasonal and interannual scales.

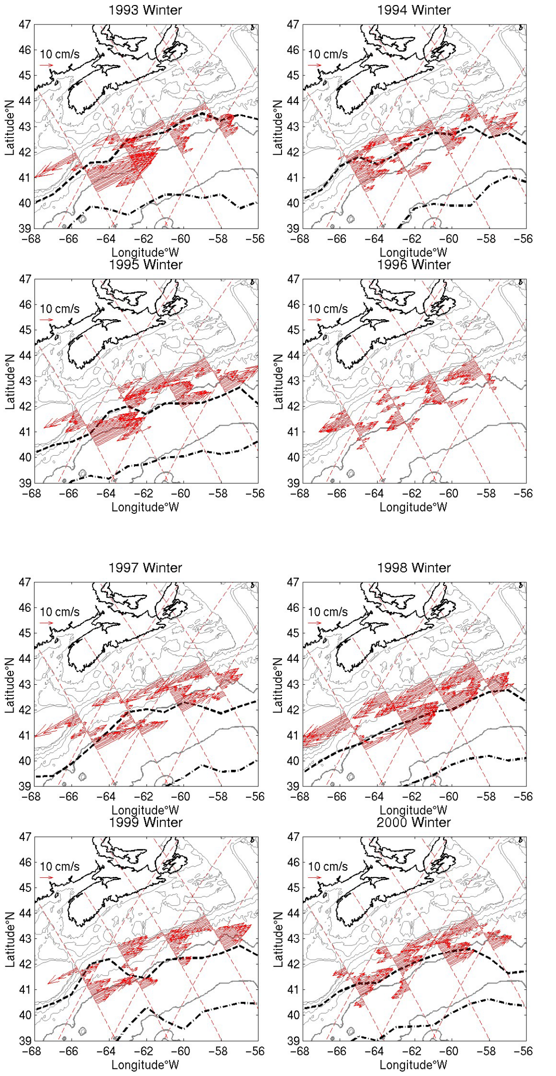


Fig. 11 Winter current fields from altimetric anomalies and Han et al.'s (1997) model means over the Scotian Slope. Also depicted are positions of the shelf/slope front (think dashed line) and the Gulf Stream northern wall (dash-dotted line) in individual winters.

The altimetric current anomaly variability increases westward and offshore. The Scotian Slope features periodic occurrence of the Gulf Stream warm core rings, whose rotational speeds can exceed 1 m/s. The increased current variability is associated with high occurrence of the anticyclonic rings. The inclusion of the model mean current does not increase the current rms values significantly, except over the shelf edge. The shelf edge current is larger in winter and smaller in summer. There is pronounced interannual variability of slope water currents in the 1990s, with the winter currents weakest in 1996 and strongest in 1998. The T/P currents are consistent with frontal analysis data, ADCP measurements, and CTD observations.

The geostrophic current anomaly normal to the T/P ground track is expected to be an underestimate of the total geostrophic current anomaly due to the neglect of the along-track current component (dependent on sea surface anomalies normal to the track). T/P data at crossovers of descending and ascending tracks allow us to estimate total rms current variability at those locations (Fig. 12). We have interpolated spatially and temporally geostrophic current anomalies normal to descending and ascending tracks to generate time series at crossovers. The normal-to-track components are then transformed into the eastward and northward components. The total rms current variability is the square root of the sum of the mean square values. Inclusion of wind-driven currents and mean flows would likely increase the peak magnitudes of the total near-surface current.

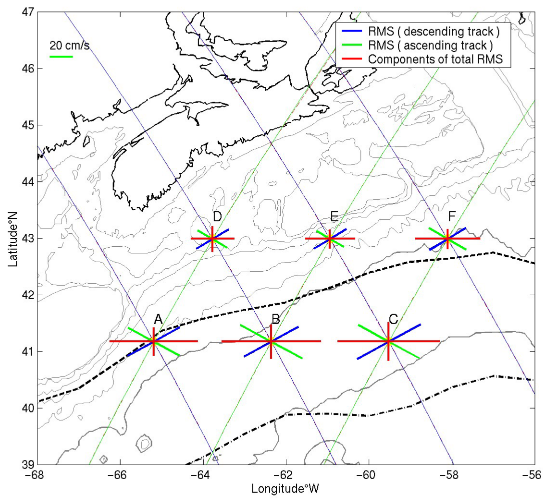


Fig. 12 Altimetric current variability at crossovers, shown as twice the rms values. Also depicted are positions of the shelf/slope front (thick dashed line) and the Gulf Stream northern wall (dash-dotted line) for the study period.

The altimetry data are most useful in quantifying the near-surface geostrophic current variability associated with anomalies in sea surface slope. Estimates of geostrophic currents at depth could be obtained by combining altimeter data with appropriate hydrographic data when available (Han and Tang, 1999). CTD sections coincident with selected cross-slope tracks should be implemented.

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