SCOTIAN SLOPE CURRENT VARIABILITY FROM TOPEX/POSEIDON ALTIMETRY

Guoqi Han

Biological and Physical Oceanography Section
Northwest Atlantic Fisheries Centre
Fisheries and Oceans Canada
St. John's, NL
Canada A1C 5X1

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ABSTRACT

G. Han. 2002. Scotian Slope Current Variability from TOPEX/Poseidon Altimetry. Can. Tech. Rep. Hydrogr. Ocean Sci. 224: viii + 36 p.

TOPEX/Poseidon sea level data from middle 1992 to early 2000 are analysed to investigate sea-surface current variability over the Scotian Slope. We first treat 1–second sea level data with de-spiking and smoothing in the along-track direction, and then calculate sea level anomalies relative to local means for this period. 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. Derived currents are analysed for spatial and temporal variability. Statistical analyses are carried out based on topographic regimes for longshore and cross-shore variability of the Slope Current. 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 warm core rings and with the proximity to the Gulf Stream. The rotational speeds of these rings often exceed 1 m/s. Seasonal and interannual variabilities are also examined. The slope circulation from the altimetric observations is strongest in winter/fall and weakest 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.

RÉSUMÉ

G. Han. 2002. Scotian Slope Current Variability from TOPEX/Poseidon Altimetry. Can. Tech. Rep. Hydrogr. Ocean Sci. 224: viii + 36 p.

Entre le milieu de 1992 et le début de 2000, on a recueilli des données TOPEX/Poseidon sur le niveau de la mer afin d'examiner la variabilité des courants à la surface de l'océan sur le talus Néo-Écossais. Les données pour 1 seconde sont d'abord écrêtées et nivelées dans la direction de la trajectoire sur le talus, puis les anomalies du niveau de la mer sont calculées en fonction des moyennes locales enregistrées pendant cette période. Les anomalies géostrophiques des courants de surface perpendiculairement aux trajectoires au sol sont dérivées à partir des anomalies du niveau de la mer. Les solutions d'un modèle régional de circulation par éléments finis permettent également de déterminer les courants de surface moyens climatologiques qui sont normalement observés à la verticale des trajectoires au sol. On superpose les moyennes du modèle et les anomalies altimétriques des courants afin de produire des courants absolus nominaux. Les courants ainsi dérivés sont analysés pour déterminer la variabilité spatiale et temporelle. Des analyses statistiques basées sur les régimes topographiques sont effectuées pour obtenir la variabilité des courants le long du littoral et perpendiculairement au littoral sur le talus. Les résultats altimétriques indiquent la principale variabilité des courants sur le talus Néo-Écossais, qui s'intensifie vers l'ouest et le sud. L'intensification serait attribuable aux nombreux anneaux à noyau chaud dans le

Gulf Stream ainsi qu'à la proximité du Gulf Stream. La vitesse de rotation de ces anneaux dépasse souvent 1 m/s. On examine également les variabilités saisonnières et annuelles. D'après des observations altimétriques, la circulation sur le talus est à son maximum pendant l'hiver et l'automne et à son minimum pendant l'été et le printemps. En outre, la présente analyse indique que la plus forte circulation hivernale a été enregistrée en 1998 et que la plus faible a été observée en 1996. Les courants altimétriques correspondent aux données d'analyse frontologiques, aux observations ADCP et CTP, ainsi qu'aux résultats du modèle numérique.

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 found that the Labrador Current transport and the Gulf Stream position experienced significant interannual changes in the past decade.

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 currents and circulation in the Slope Water region is limited, particularly over the Scotian Slope. Recent mooring projects initiated under DFO/PERD programs 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 front 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 offshore oil and gas activities in the deep waters of the Scotian Slope.

In section 2, we describe the 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. Four T/P ascending tracks and three 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:

1) wet troposphere delay measured by the T/P microwave radiometer;
2) dry troposphere delay determined from the European Centre for Medium-Range Weather Forecasts surface pressure model;
3) ionosphere delay based on the dual frequency altimeter measurement;
4) electromagnetic bias (due to ocean wave influences) using 2% of the significant wave height;
5) inverse barometric response of sea surface height to atmospheric pressure change; and
6) ocean, load, solid Earth, and pole tides.

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 with an along-track 3-point median filter. 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. 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. The sea surface height anomalies for Track 071 are shown in Figure 2 for October 20, 1999 and in Figure 3 for August-November 1999.

2.2 Derivation of surface current anomalies

From the T/P sea surface height anomalies, geostrophic surface currents normal to the track (Figs. 2 and 3, 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 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. We can see a southwestward flow along the shelf edge and the upper continental slope and a northeastward 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.

2.3 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 (e.g., Drinkwater et al., 1994). 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". After digitization, the positions of the northern boundary of the Gulf Stream and the Shelf/Slope front were averaged at each degree of longitude for each chart.

As an example, Figure 5 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 Water, and warm temperature patches with some of them associated with Gulf Stream warm core rings (WCR), for the week of August 21, 1995. A Gulf Stream ring is apparent over the continental slope off Georges Bank and the western Scotian Shelf (where Tracks 071 and 012 cross).

3. Results

3.1 General description

The sea surface height anomalies on Track 071 (Fig. 3) show large along-track variations in the Slope Water region (39-42°N), associated with fluctuations in the Gulf Stream position and the occurrence of WCRs. The associated current anomalies (normal component) often have magnitudes of order 1 m/s, particularly south of 42 °N (Fig.3). Anticyclonic ring circulation apparently occurred in September-October 1999 between 40 and 42 °N, indicated by the negative (eastward) current anomalies around 41°N between September 11 and October 20.

There are significant interannual variations in the current anomalies, as seen in time series of the anomalies near the 1000- and 4000-m isobaths (Fig. 6) on the descending tracks that are approximately normal to the shelf edge (Fig. 1). 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.

Figure 7 shows the root mean square (rms) values of the altimetric sea level anomalies. There is generally increased variability as one proceeds offshore towards the Gulf Stream. Typical values are 10 cm over the upper slope. The magnitude increases westward, particularly over the lower slope and continental rise.

Figure 8 shows the spatial distribution of 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 WCR activity to the west (Fig. 9). 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. The RMS values for the four bands for each track also demonstrate the decrease in anomaly strength with distance from the Gulf Stream.

To provide further statistical information on the spatial structure of the current anomalies on the 4 cross-slope tracks, four along-track bands were selected based on bathymetry: (i) 200-1000m (referred to as upper slope), (ii) 1000-3000m, (iii) 3000-4000m (referred to as lower slope) and (iv) 4000-4500m (referred to as continental rise). Fig. 10 presents percentage occurrence of currents for the four bands and shows the rms values of the altimetric current anomalies. Overall, the variability is strongest with higher occurrence of extreme currents on Tracks 012 and 071 off Northeast Channel and Georges Bank, and weakest with lower occurrence of extreme currents on Track 126 off Sable Island Bank (also see Table 1).

The inclusion of the present model mean currents does not change the statistics significantly (especially over the lower slope), indicating the eddy kinetic energy is overwhelmingly dominant over the mean kinetic energy for the Scotian Slope surface circulation. Nevertheless, It is 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.

3.2 Seasonal variability

The T/P sea level anomalies at each location are averaged monthly and over all years and plotted in the month-latitude domain for each track (Fig. 11). There are large seasonal changes, higher in summer and lower in winter. The magnitudes generally increase westward and offshore. Typical ranges are 10 cm for the upper slope, and up to 20 cm for the lower slope. The seasonal cycle seems to be associated with the thermal expansion and contraction as a result of solar heating and advection and possibly with the south-north movement of the Gulf Stream position. The monthly means are not only consistent with the annual sea level harmonic of Han et al. (2002), but also provide more information on intra-seasonal variability.

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. 12) 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 strongest in winter/fall and weakest in spring/summer. The seasonal range amounts to 10-20 cm/s. The eastward slope current (with the mean current toward the northeast (Fig. 4)) over the lower continental slope in the vicinity of 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.

3.3 Interannual variability

For each cross-slope ground track, the T/P sea level anomalies at each location are first averaged seasonally and then averaged spatially for the four slope segments based on bathymetry: (i) 200-1000m, (ii) 1000-3000m, and (iii) 3000-4000m and (iv) 4000-4500m. The seasonal, spatially averaged anomalies are further smoothed using a temporal 5-point moving filter.

Over the lower continental slope and rise, the sea level variation had a pronounced interannual cycle, with an increasing magnitude towards deeper waters (Fig. 13). Sea level variations on all the four tracks showed a significant sea level fall from 1994 to 1996, with a rapid rebound after 1997. The sea level range amounts to 10-20 cm. However, notable differences among the tracks exist in sea level fluctuations at shorter time scales. Over the shelf edge and upper continental slope between the 200- and 1000-m isobaths, the sea level variability is much less. In fact, the sea level change over the Scotian Slope was almost out of phase with that over the Scotian Shelf (Han, 2002).

To illustrate details of the cross-shelf structure of sea level variation, we examined the time-latitude plot of sea level for the central and western Scotian Shelf tracks (Fig. 14). The sea level up/down is highly coherent across the slope. The difference between the shelf and slope is significant in certain periods. In particular, there were large sea surface slope anomalies (upwards toward the coast) over the shelf edge and the upper continental slope in 1997 and early 1998, which are associated with intensified shelf-edge currents (Fig. 15) during this period since the mean shelf-edge flow is directed southwestward (Fig. 4).

4. Evaluation

4.1 Frontal analysis

Altimetric data indicate anti-cyclonic gyres from time to time. These circulation features are apparently associated with warm patches of surface water revealed from infrared images. When there were WCRs indicated in the frontal analysis data, the altimetric data also show anticyclonic gyres in the same location (Fig. 16; Fig.17a). The geostrophic currents associated with these gyres can be over 1 m/s. These rings 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.

4.2 ADCP and CTD data

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 are presented in Fig. 17b. We can see approximate agreement of the eastward current on the northern side of the ring. Figure 18 shows the temperature distribution from CTD (Conductivity-Temperature-Depth) data, which clearly shows that the temperature is above 18° and 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).

4.3 Hydrodynamic model results

Fig. 19 presents Han et al.'s (1997) seasonal-mean currents over the Scotian slope. The model rms current magnitude is 11.3, 8.9, 10.1 and 12.8 cm/s for winter, spring, summer and fall, respectively. In general, the model results show stronger southwestward shelf edge flow and northeastward Slope Water current in winter/fall, similar to the altimetry results in Fig. 12. However, there are notable discrepancies in some areas. The model-altimetry rms current difference is 8.3, 6.4, 8.5 and 4.9 cm/s for winter, spring, summer and fall, respectively. Note that the altimetry results provide geostrophic current estimates for the period from 1992 to 2000, and the model solutions represent climatological seasonal-mean realization diagnosed from density data.

5. Summary and Discussion

We have used T/P altimeter data for the period from 1992 to 2000 to study sea level and 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.

The altimetric current anomaly variability increases westward and offshore. The Scotian Slope features periodic occurrence of the Gulf Stream warm core rings. 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 variability significantly, except over the shelf edge.

The sea level is higher in summer and lower in winter, with larger magnitude offshore. The shelf edge current is larger in winter and smaller in summer. There is pronounced interannual variability of sea level in the 1990s, higher in early 1990s, and lowest in 1997/8, and rebound afterwards. The shelf edge current is strongest in 1997/1998.

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). Under the assumption of isotropy, the RMS values for the total geostrophic current anomaly can be estimated as those for the cross-track component multiplied by a factor of 1.4.

T/P data at crossovers of descending and ascending tracks allow us to estimate total rms current variability at those locations. 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.

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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Table 1. Percentage Occurrence of T/P-derived Cross-track Current Anomalies.

Depth (m)	Range (m/s)	Track 012	Track 050	Track 088	Track 126
200-1000	>0.25	31.8%	17.8%	17.6%	15.4%
	>0.50	6.7%	1.6%	1.7%	1.6%
	>1.00	0.1%	0.0%	0.0%	0.3%
	>1.50	0.0%	0.0%	0.0%	0.2%
1000-3000	>0.25	34.5%	20.4%	19.9%	15.3%
	>0.50	9.6%	2.6%	1.5%	1.1%
	>1.00	0.7%	0.0%	0.1%	0.0%
	>1.50	0.1%	0.0%	0.0%	0.0%
3000-4000	>0.25	35.6%	26.4%	18.0%	18.5%
	>0.50	12.1%	5.2%	2.6%	1.6%
	>1.00	1.2%	0.4%	0.3%	0.0%
	>1.50	0.1%	0.0%	0.2%	0.0%
4000-4500	>0.25	42.0%	33.7%	25.2%	22.3%
	>0.50	17.3%	12.0%	4.9%	2.7%
	>1.00	3.0%	0.4%	0.2%	0.0%
	>1.50	0.3%	0.0%	0.1%	0.0%

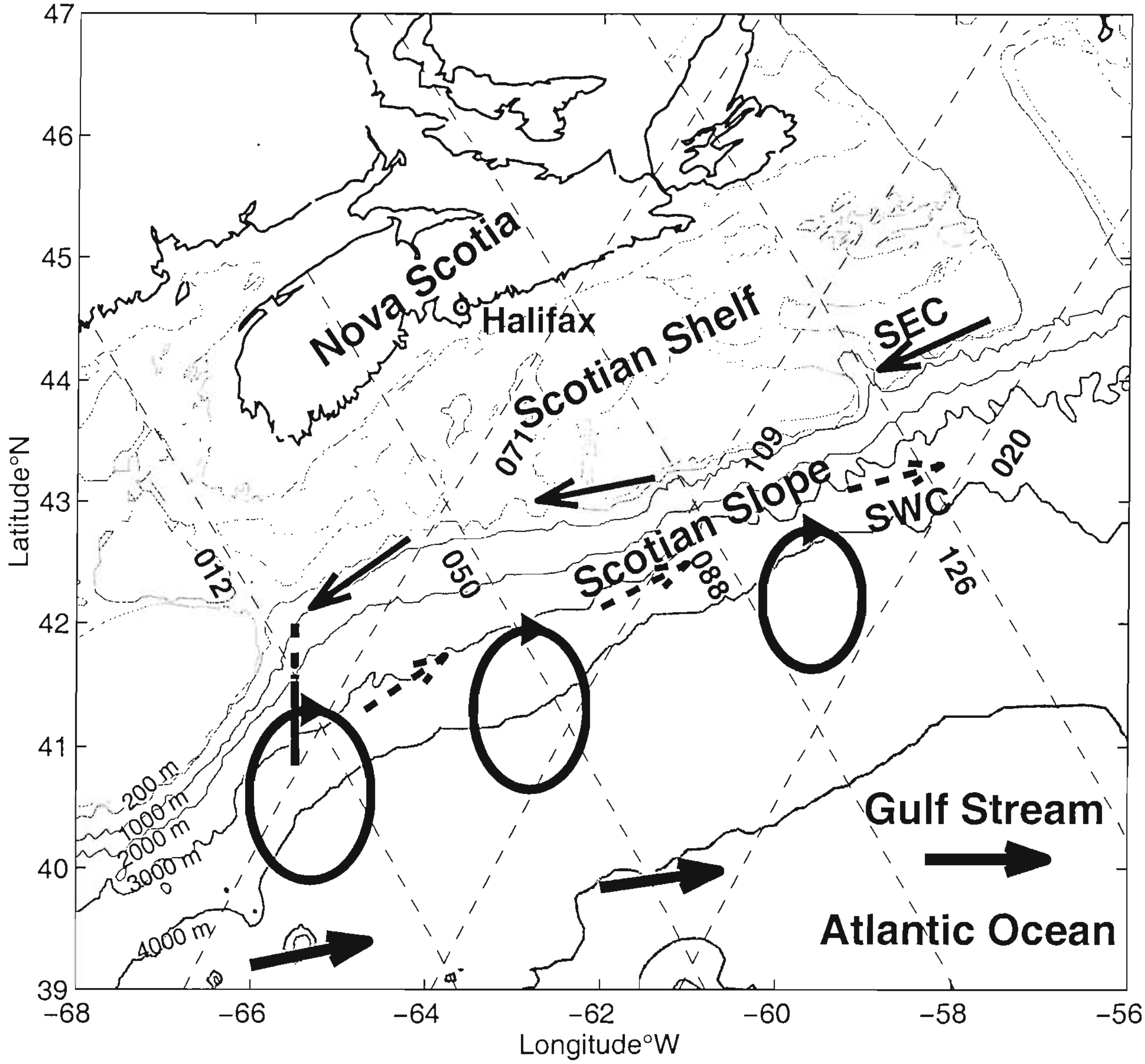


Figure 1. Map showing the Scotian Slope and adjacent shelf and deep oceans with a schematic representation of the circulation. The labeled lines are the selected T/P ground tracks on which the analysis is performed. The thick dashed line indicates the location of a hydrographic survey section. SEC: shelf-edge current; SWC: Slope Water current. Gulf Stream rings are depicted as ellipses.

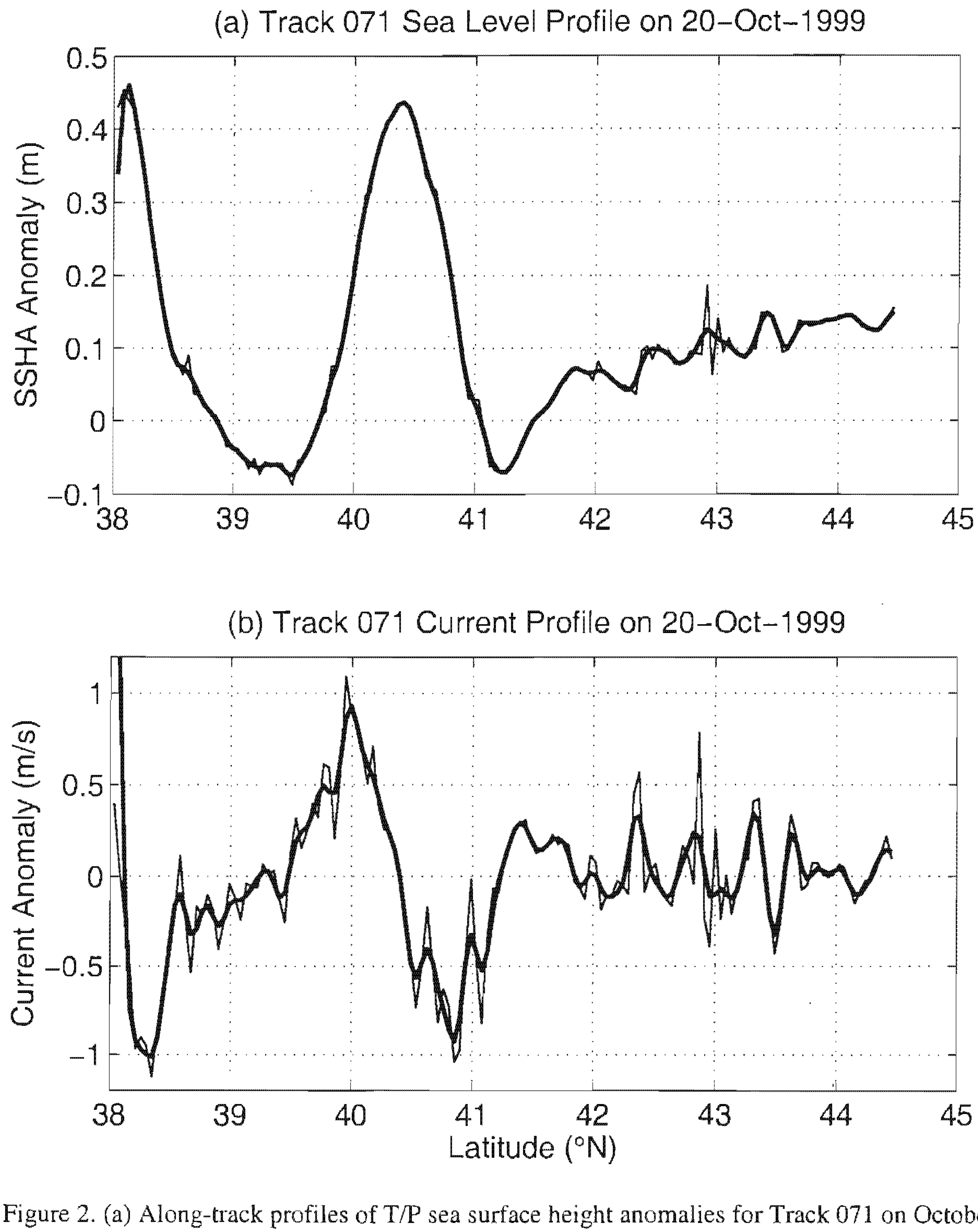


Figure 2. (a) Along-track profiles of T/P sea surface height anomalies for Track 071 on October 20, 1999: unsmoothed (thin line) vs. smoothed with the digital filter (thick line). (b) Associated cross-track geostrophic currents.

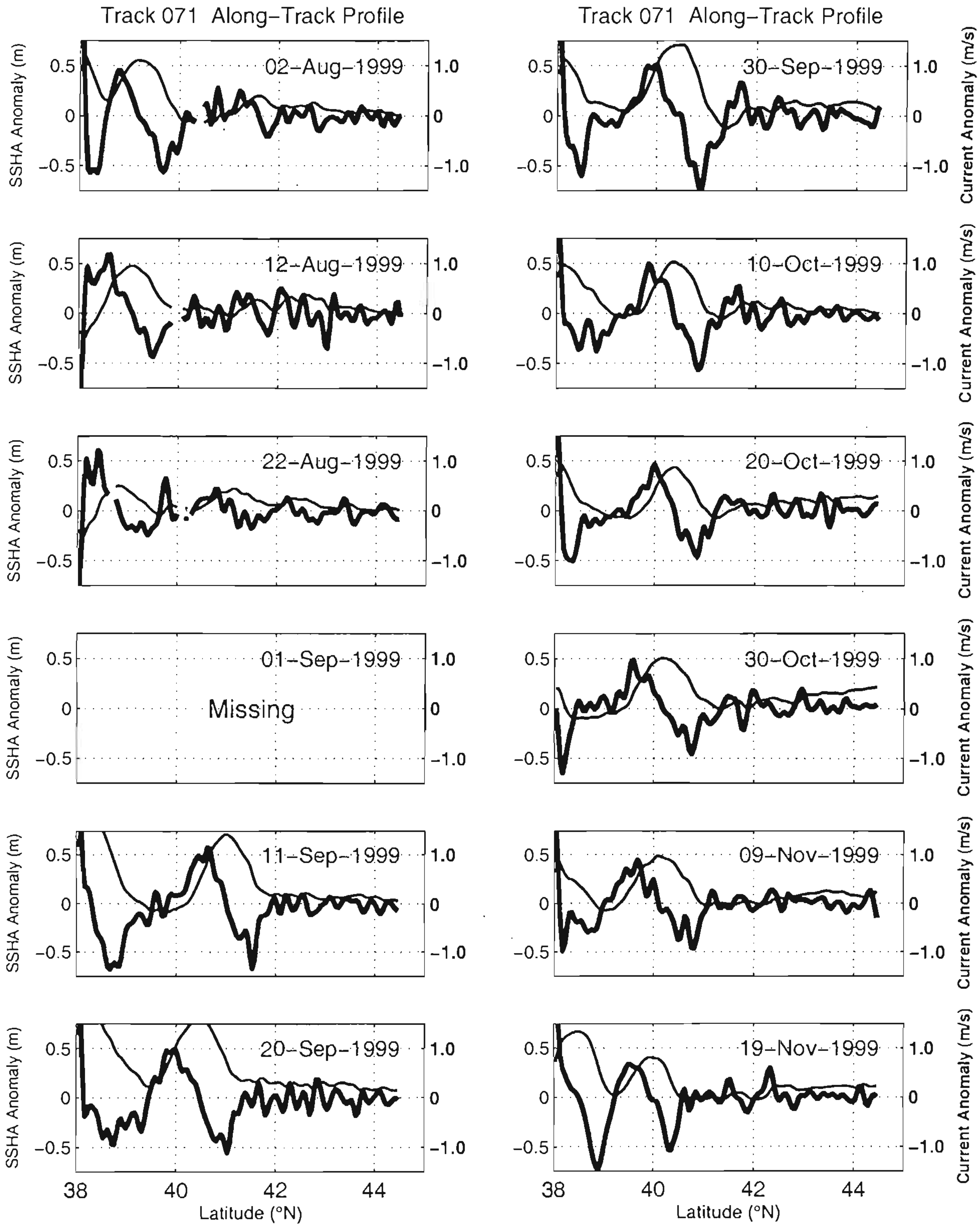


Figure 3. Along-track profiles of the smoothed T/P sea level anomalies (thin line) and associated cross-track geostrophic surface current anomalies (thick line, positive westward) for track 071 from August-November 1999.

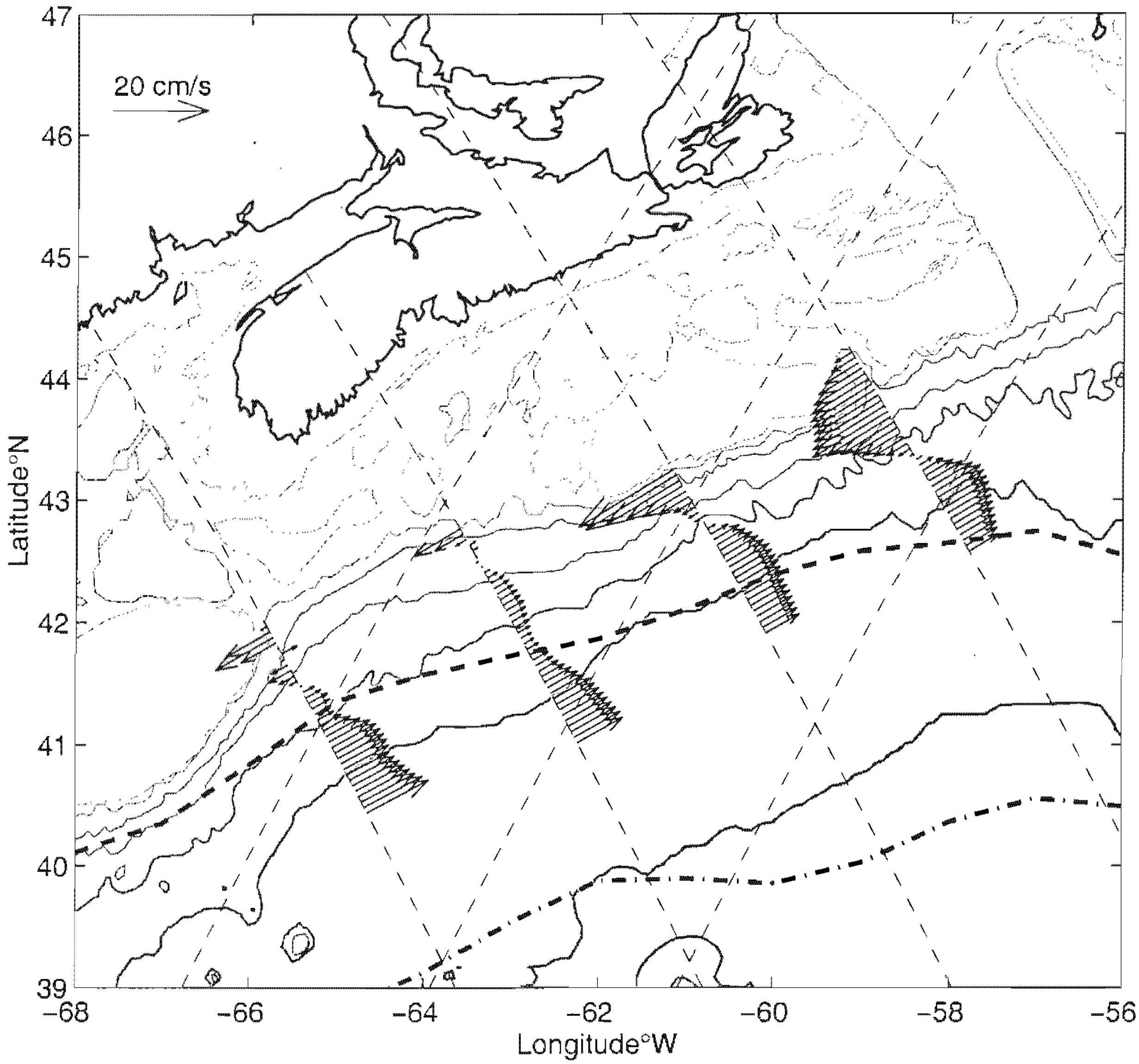


Figure 4. Climatological seasonal-mean surface currents over the Scotian Slope derived from Han et al.'s (1997) model results. Also depicted are positions of the shelf/slope front (thick dashed lines) and the Gulf Stream northern boundary (dash-dotted lines) for the study period (see the next subsection).

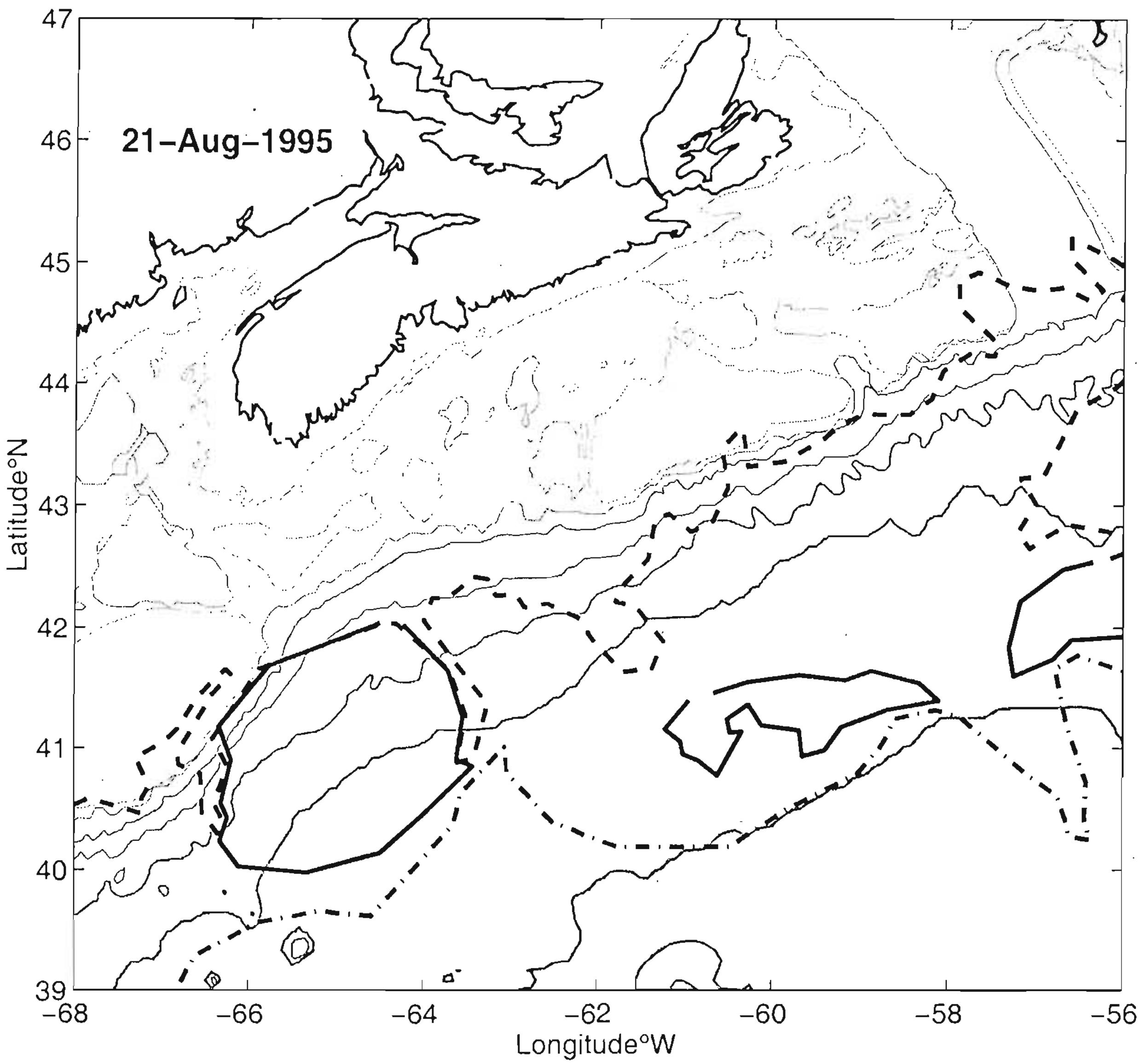


Figure 5. The positions of the Gulf Stream northern boundary (dash-dotted line) and shelf/slope front (dashed line) and the warm temperature patches of surface water (solid line) derived from satellite thermal imagery for the week of August 21, 1995.

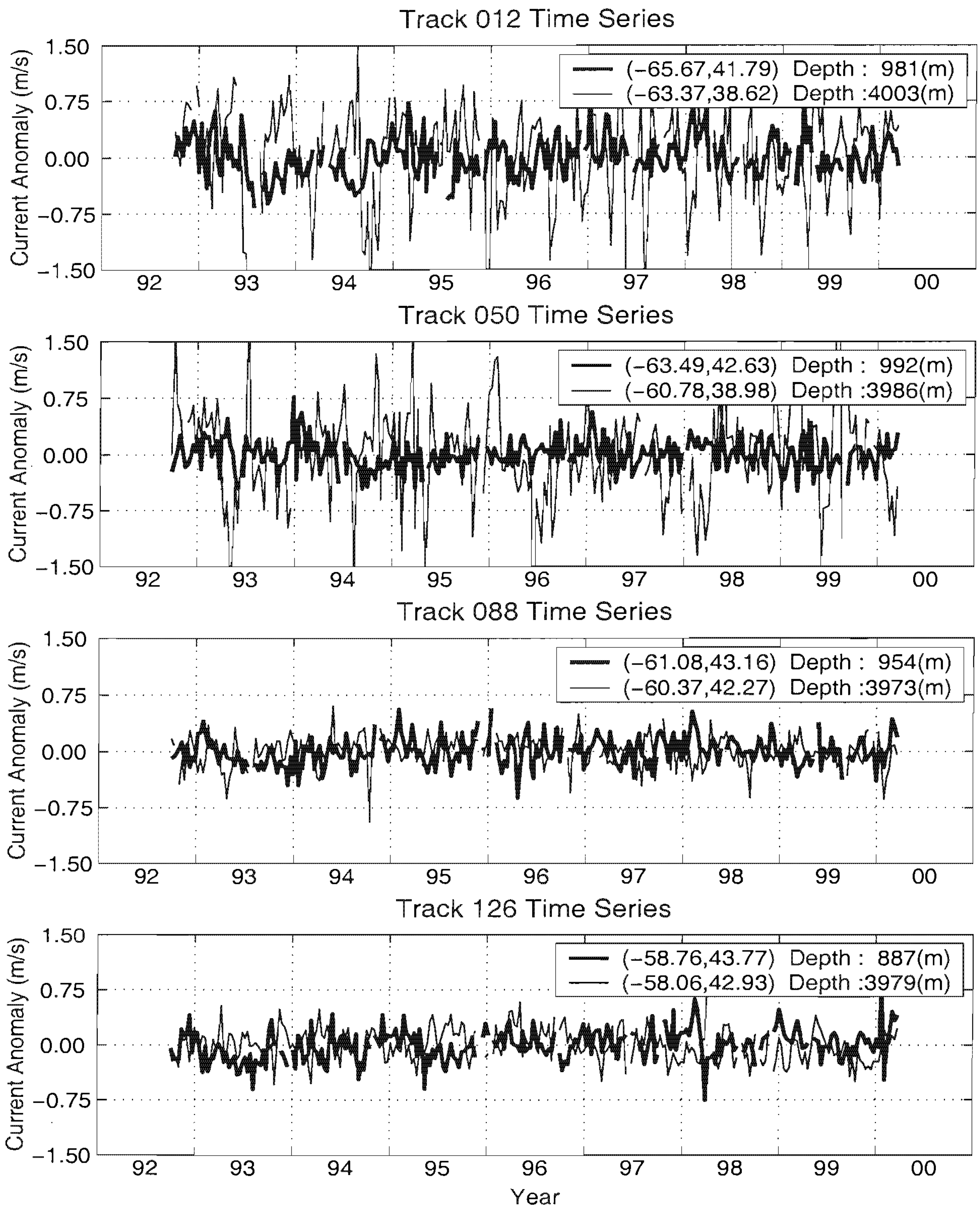


Figure 6. Time series of current anomalies at nominal 1000-m (thick line) and 4000-m (thin line) water depths on the four descending tracks.

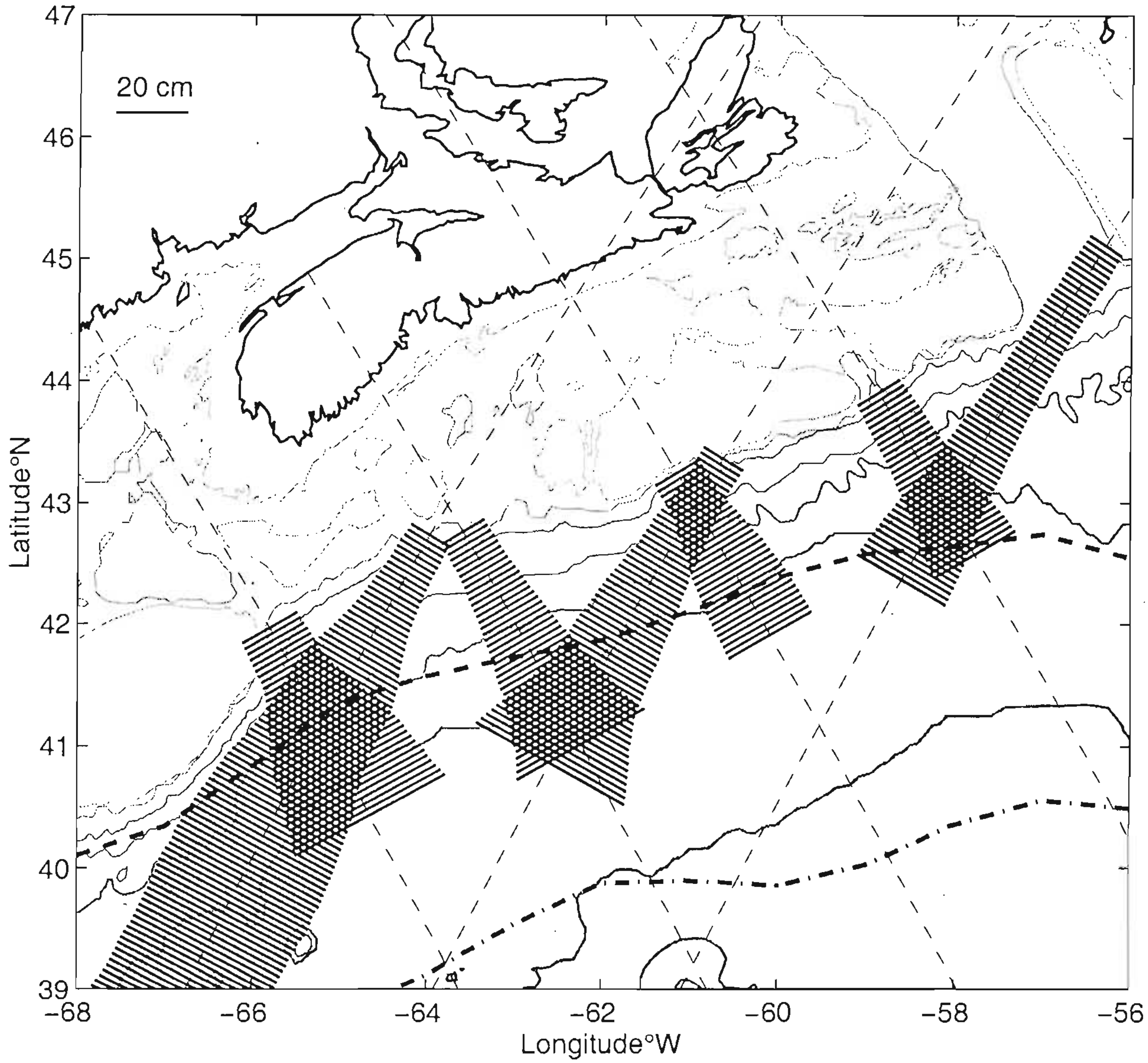


Figure 7. Sea level variability over the Scotian Slope calculated from the T/P altimetry data from 1992 to 2000 and plotted as twice the rms values. Also depicted are positions of the shelf/slope front (thick dashed lines) and the Gulf Stream northern boundary (dash-dotted line) for the period.

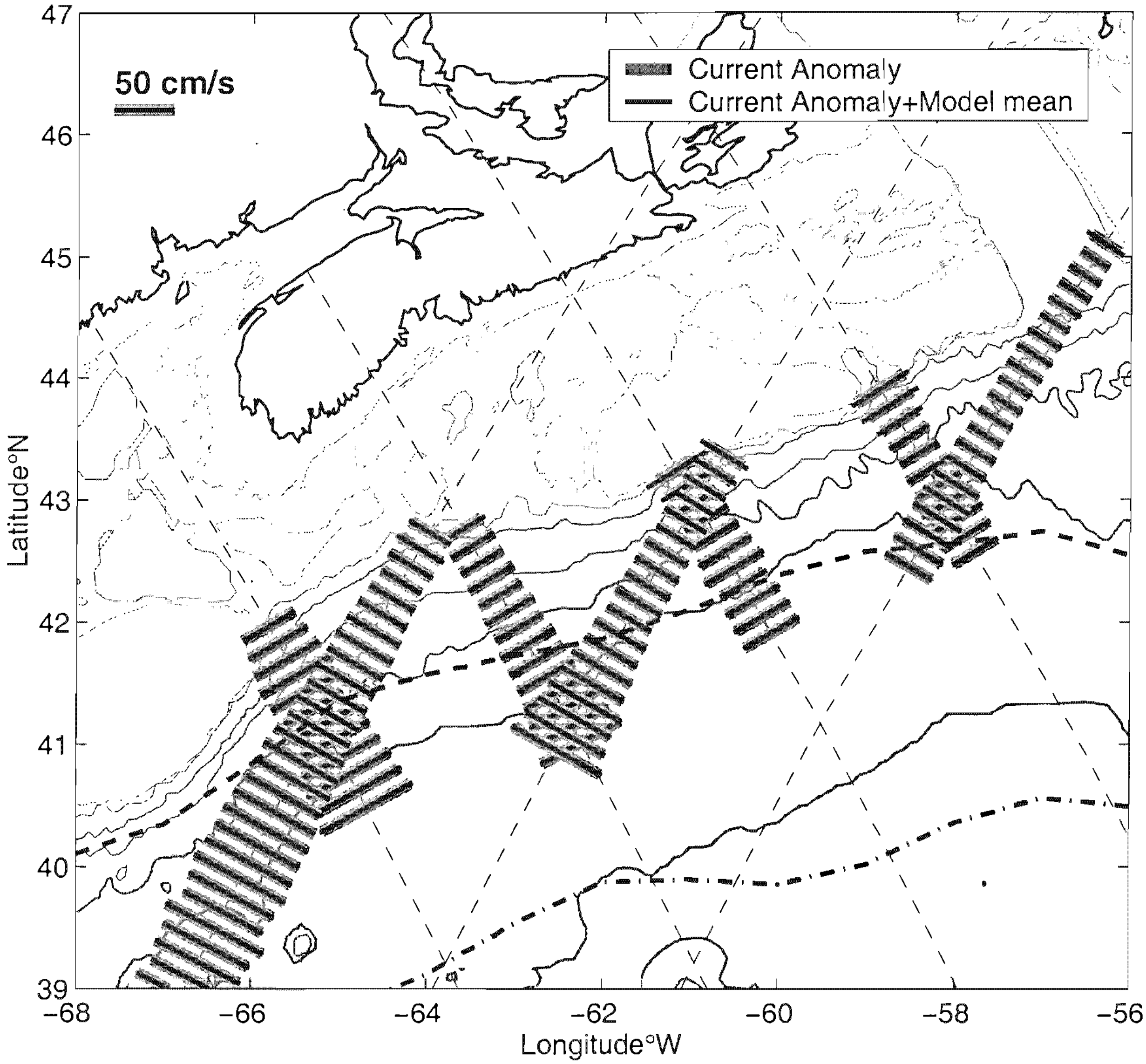


Figure 8. Variability of the altimetric current anomalies (sub-sampled spatially) from 1992 to 2000 plotted as twice the rms values (thick gray lines). The thin lines represent twice the rms values when Han et al.'s model means are included. Also depicted are positions of the shelf/slope front (thick dashed lines) and the Gulf Stream northern boundary (dash-dotted line) for the period.

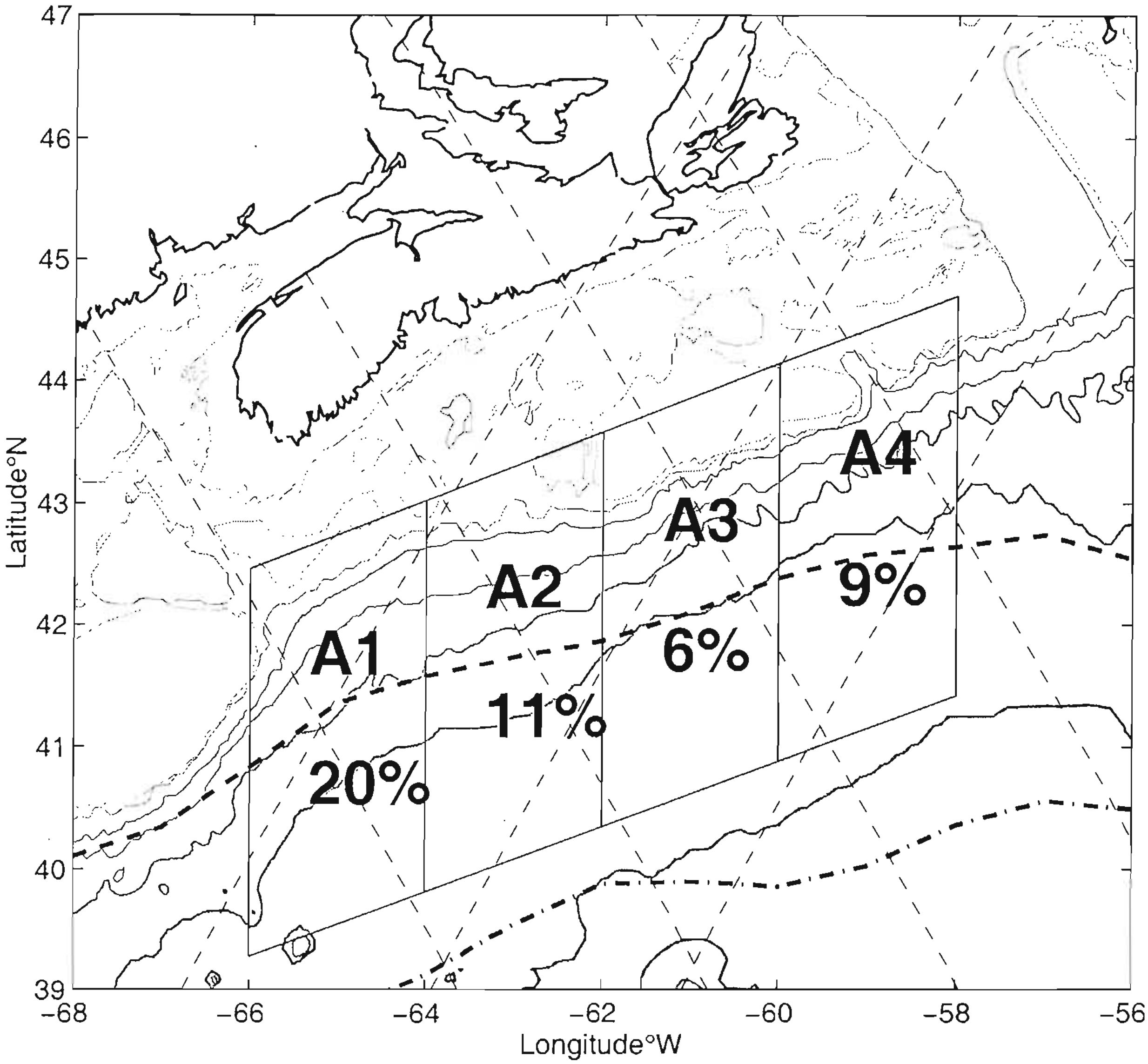


Figure 9. Percentage occurrence of WCRs over the Scotian Slope based on the frontal analysis data (K. Drinkwater and R. Pettipas, personal communication, 2001) from 1992 to 2000. A total of 989 days was included in the analysis. Also depicted are positions of the shelf/slope front (thick dashed lines) and the Gulf Stream northern boundary (dash-dotted line) for the period.

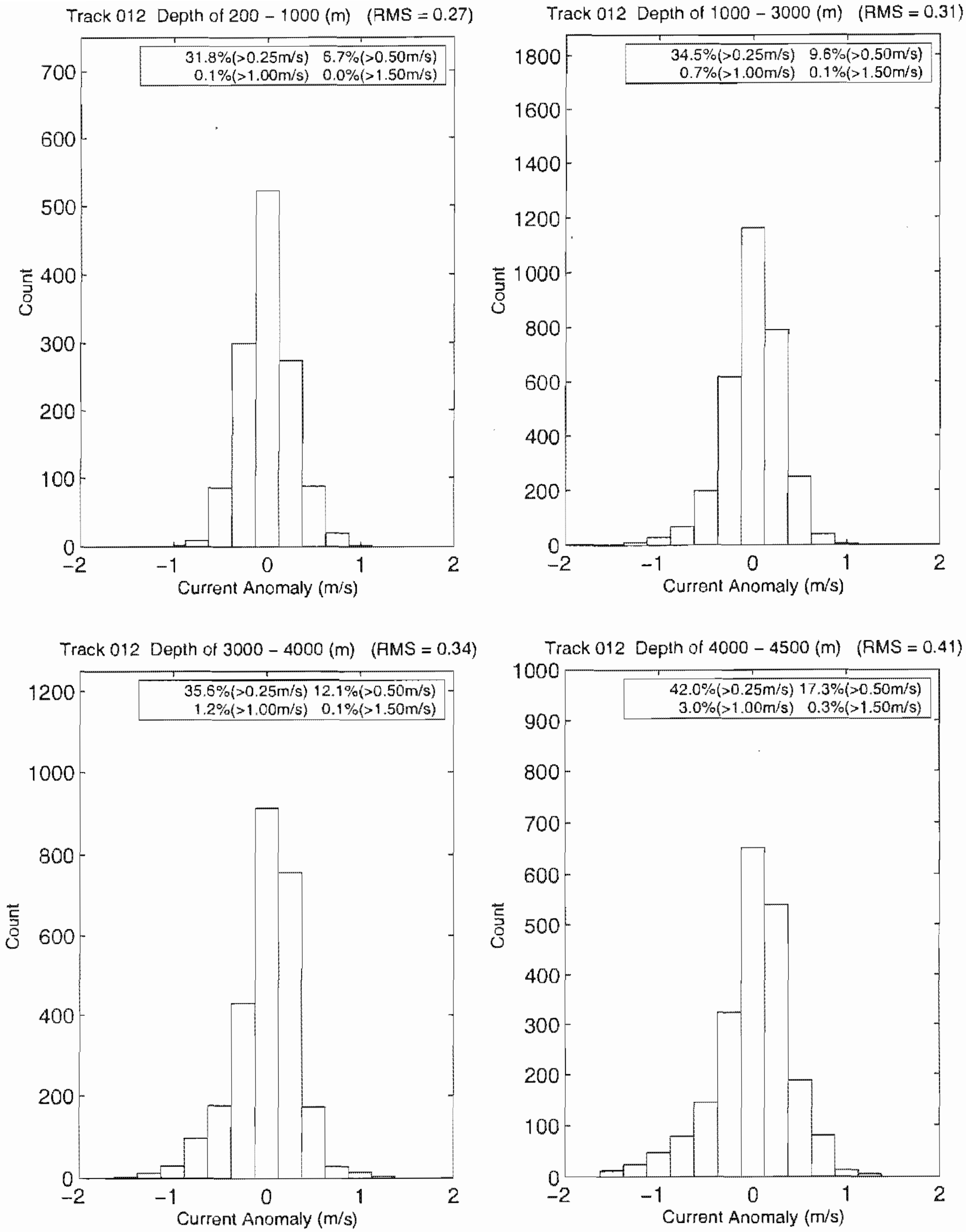


Figure 10. Histograms of the altimetric current anomalies normal to the track, for Tracks (a) 012, (b) 050, (c) 088, and (d) 126.

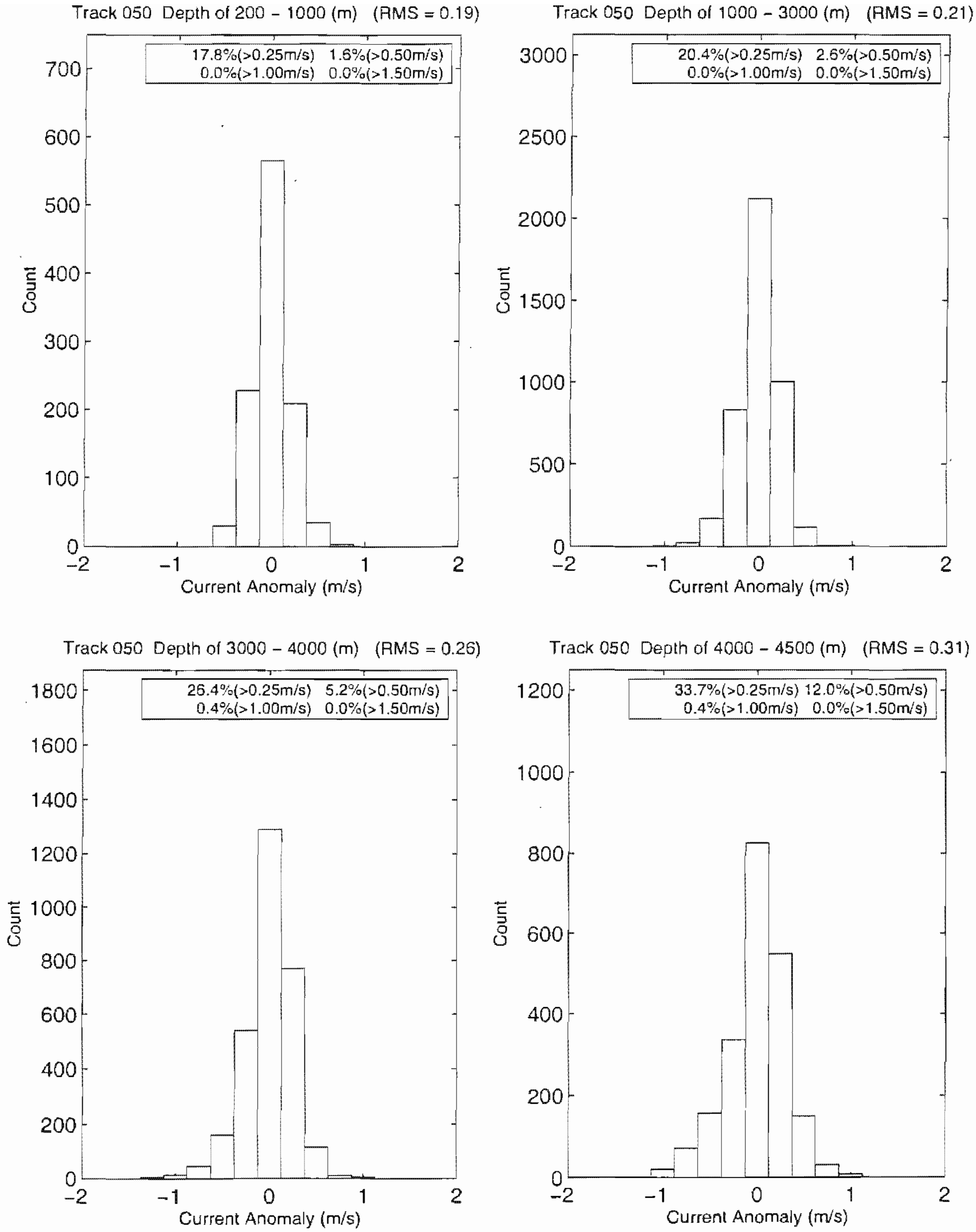


Figure 10 (continued).

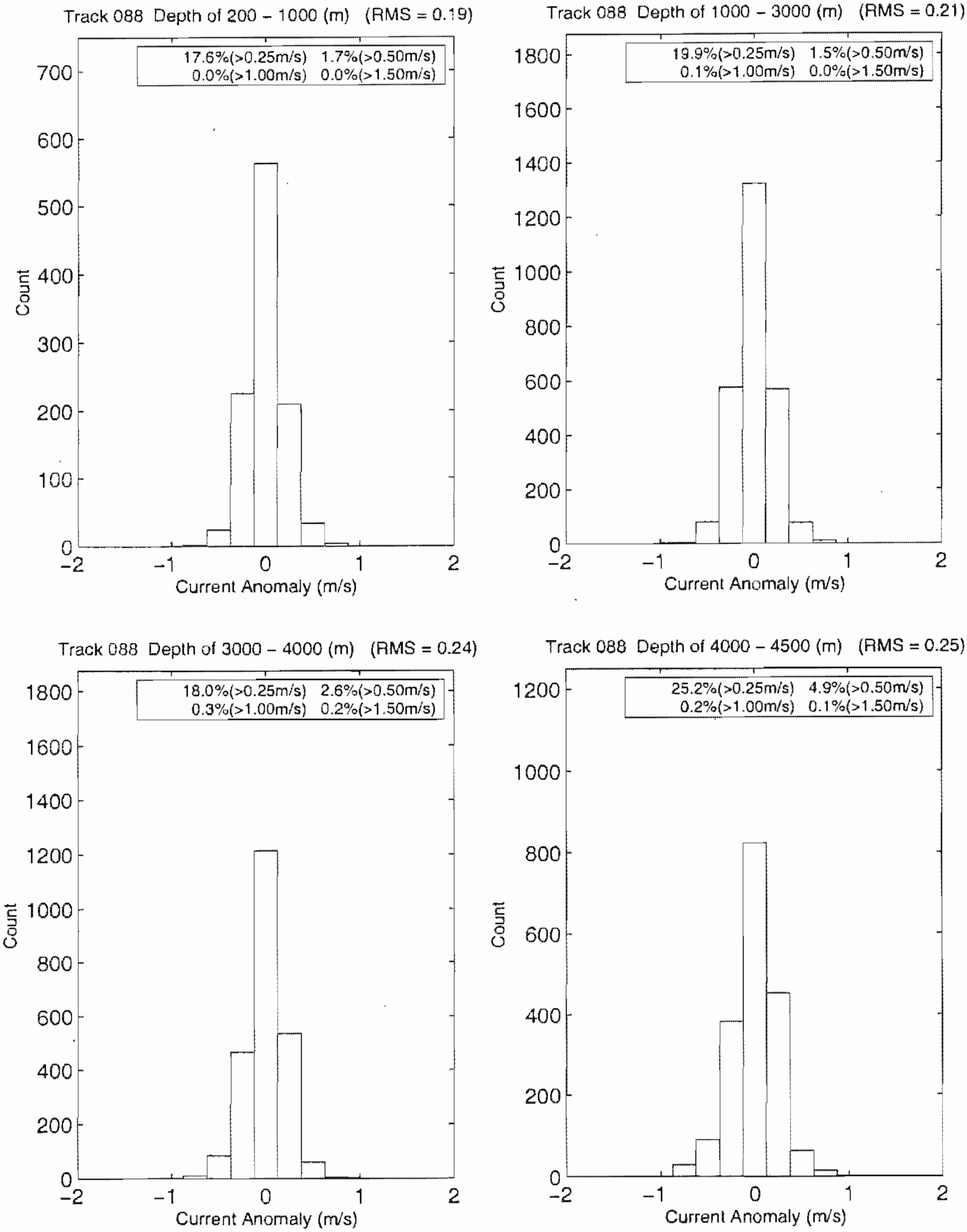


Figure 10 (continued).

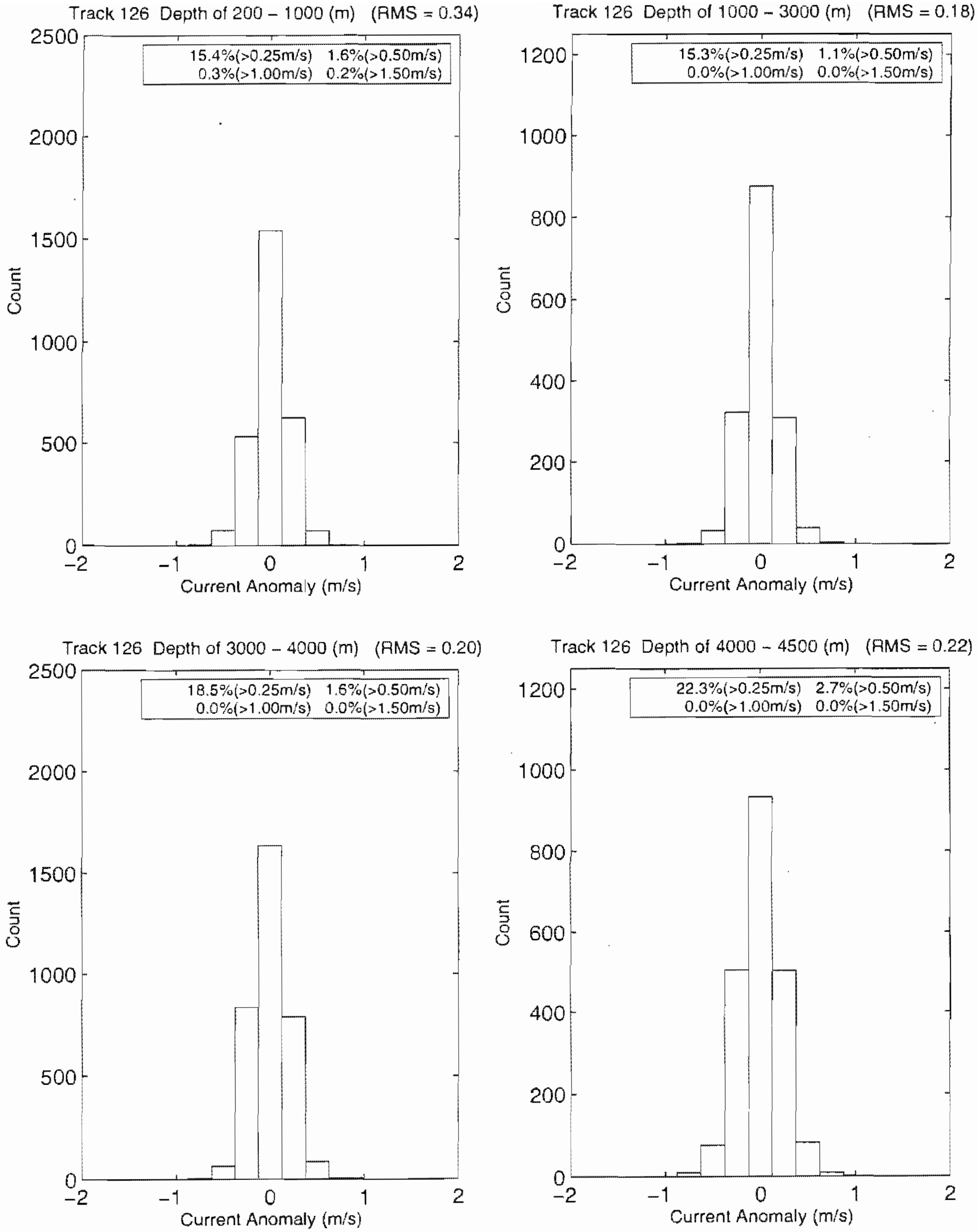


Figure 10 (continued).

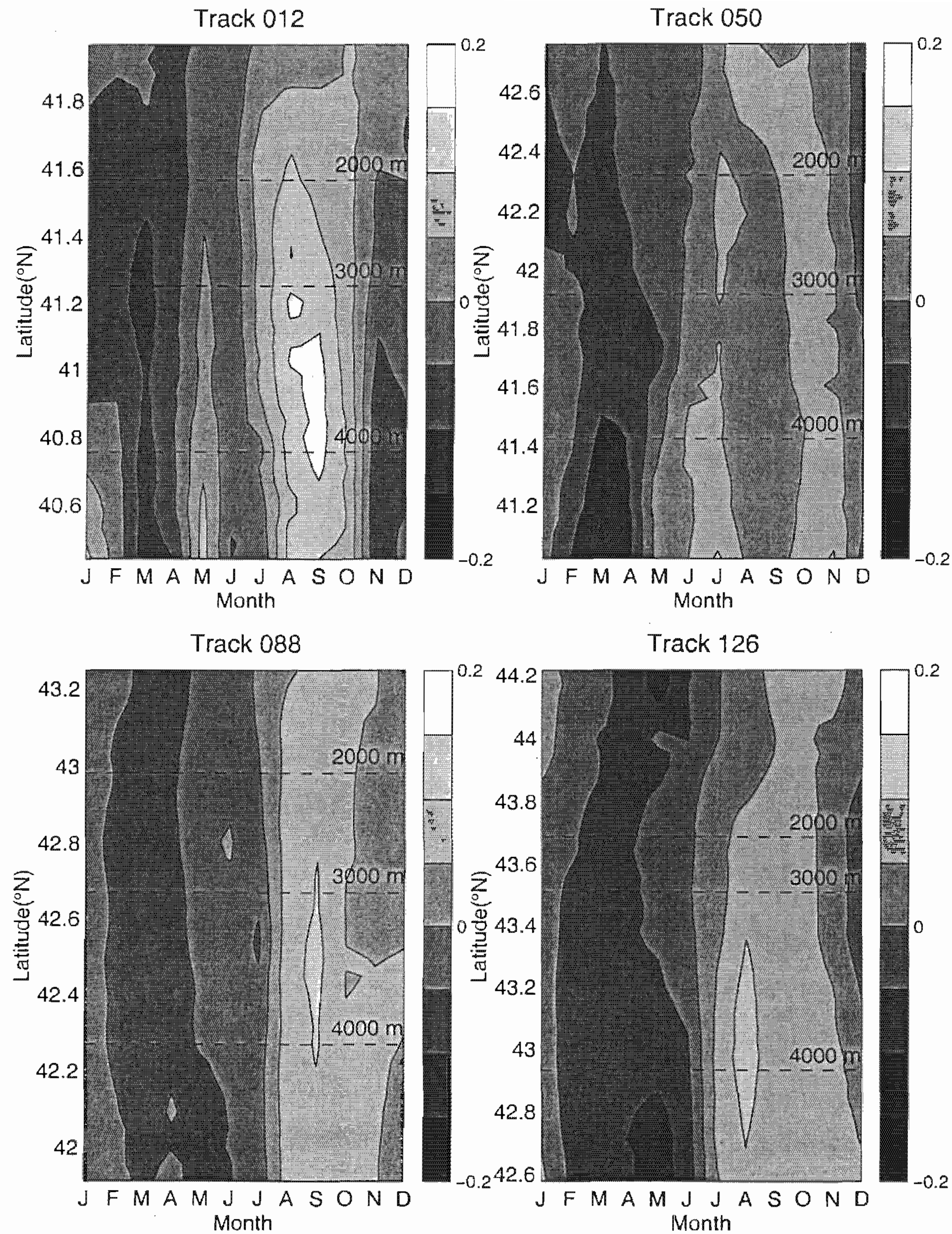


Figure 11 Along-track distribution of monthly sea level anomalies (m) from T/P data.

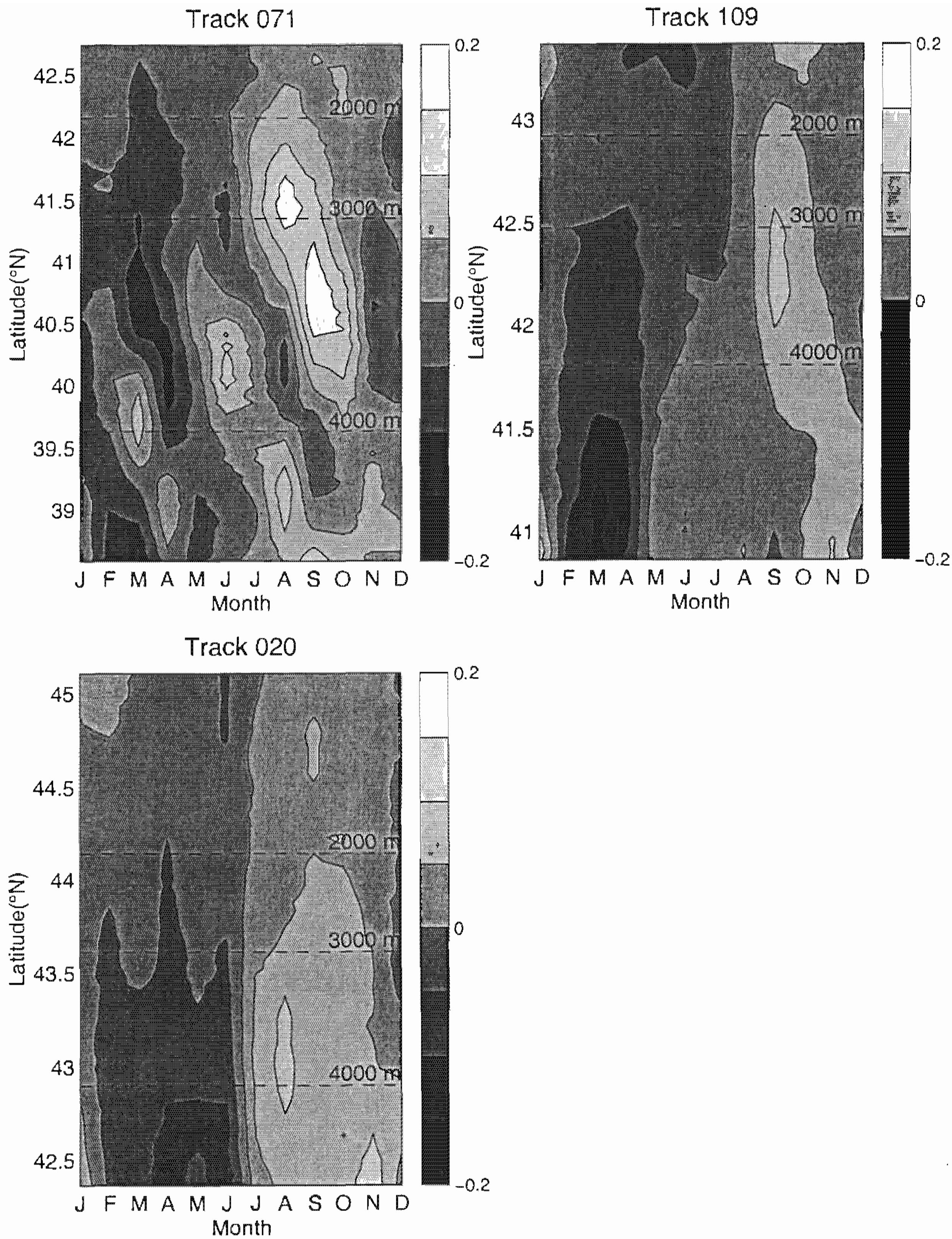


Figure 11 (continued).

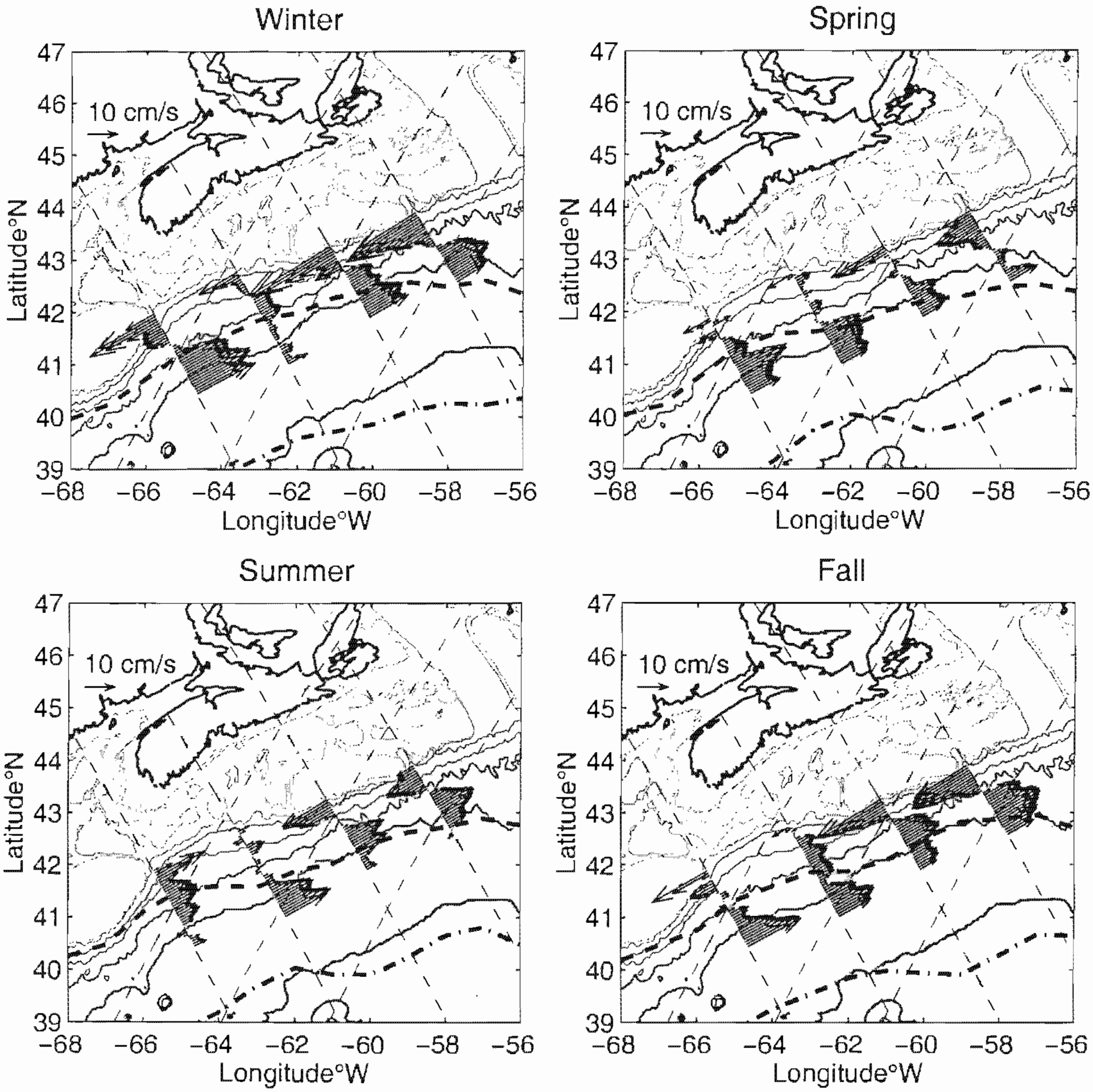


Figure 12. Seasonal-mean currents over the Scotian Slope in (a) winter, (b) spring, (c) summer and (d) fall: altimetric anomalies plus Han et al.' (1997) model means. Also depicted are positions of the shelf/slope front (thick dashed lines) and the Gulf Stream northern boundary (dash-dotted line) for each season.

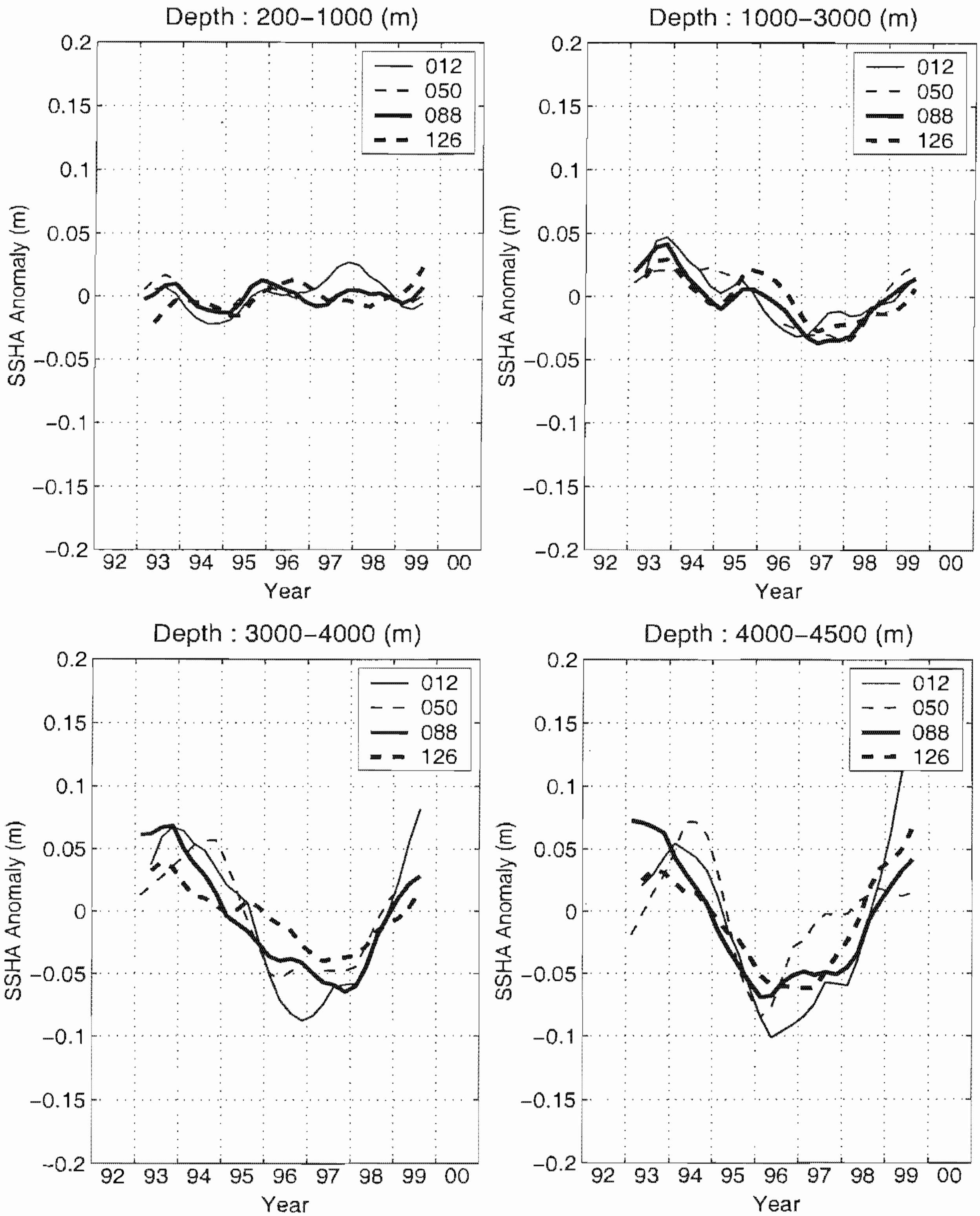


Figure 13. Seasonal T/P sea level anomalies over the Scotian Slope, averaged for four segments based on bathymetry. The seasonal means are smoothed with a five-point moving filter.

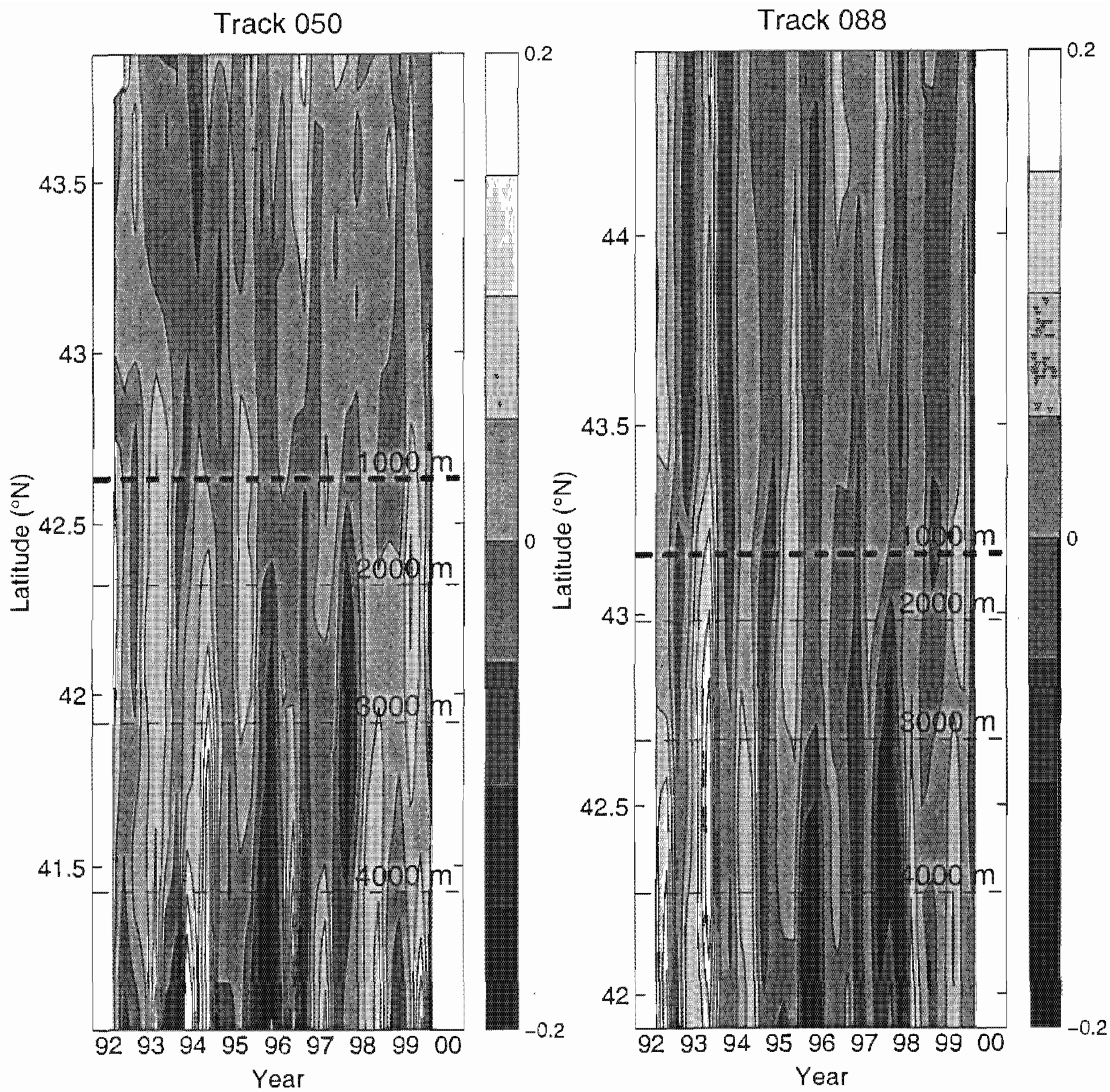


Figure 14. Seasonal T/P sea level anomaly (m) distribution over the Scotian Slope in the time-latitude domain for track 050 and 088, including both the Scotian Shelf and Slope. The seasonal mean anomalies are smoothed with a 5-point moving filter. The dashed lines indicate water depths.

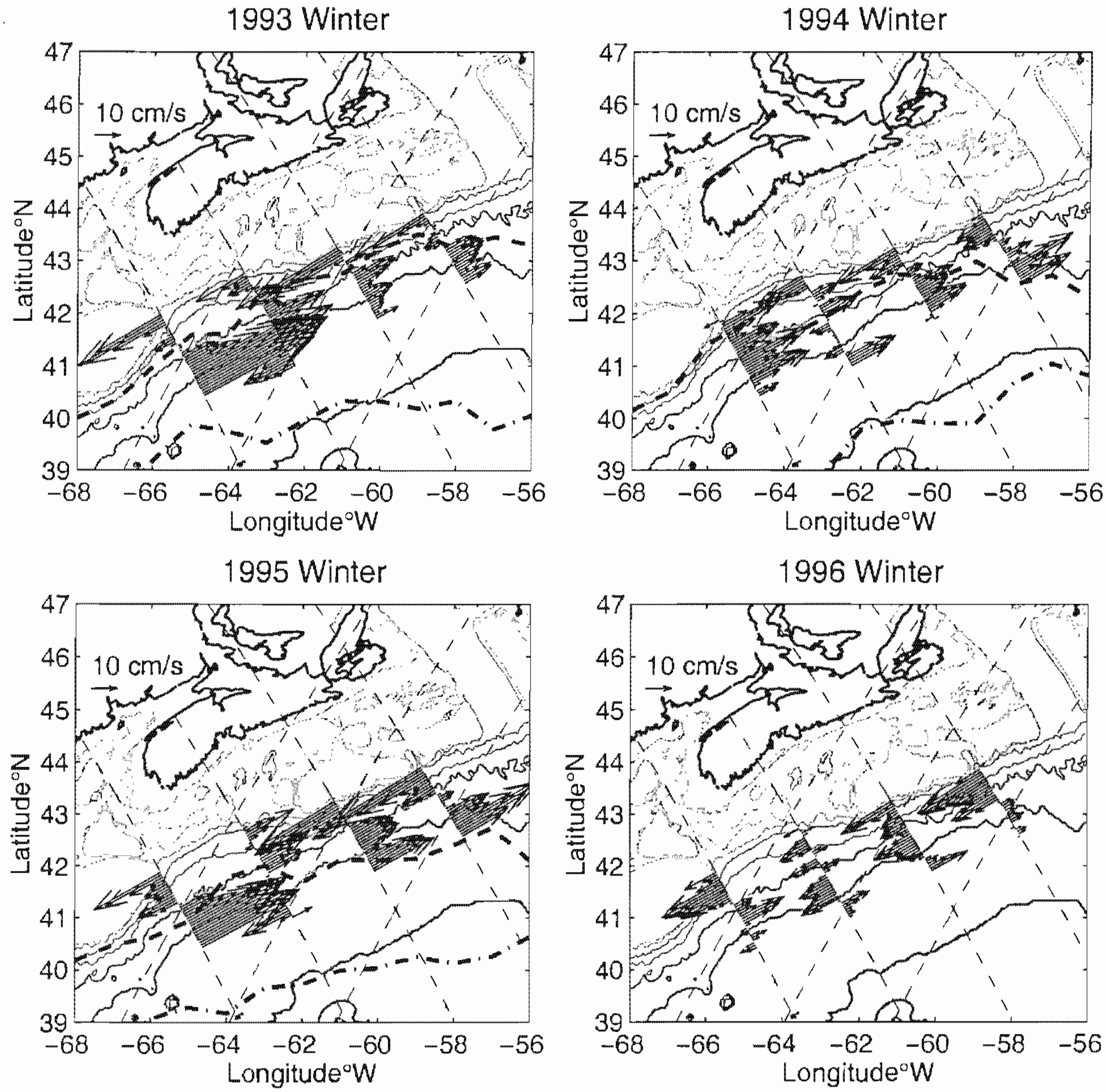


Figure 15. Winter current fields from altimetric anomalies and Han et al.'s (1997) model means over the Scotian Slope. Also depicted are positions of the shelf/slope front (thick dashed lines) and the Gulf Stream northern boundary (dash-dotted lines) in individual winters.

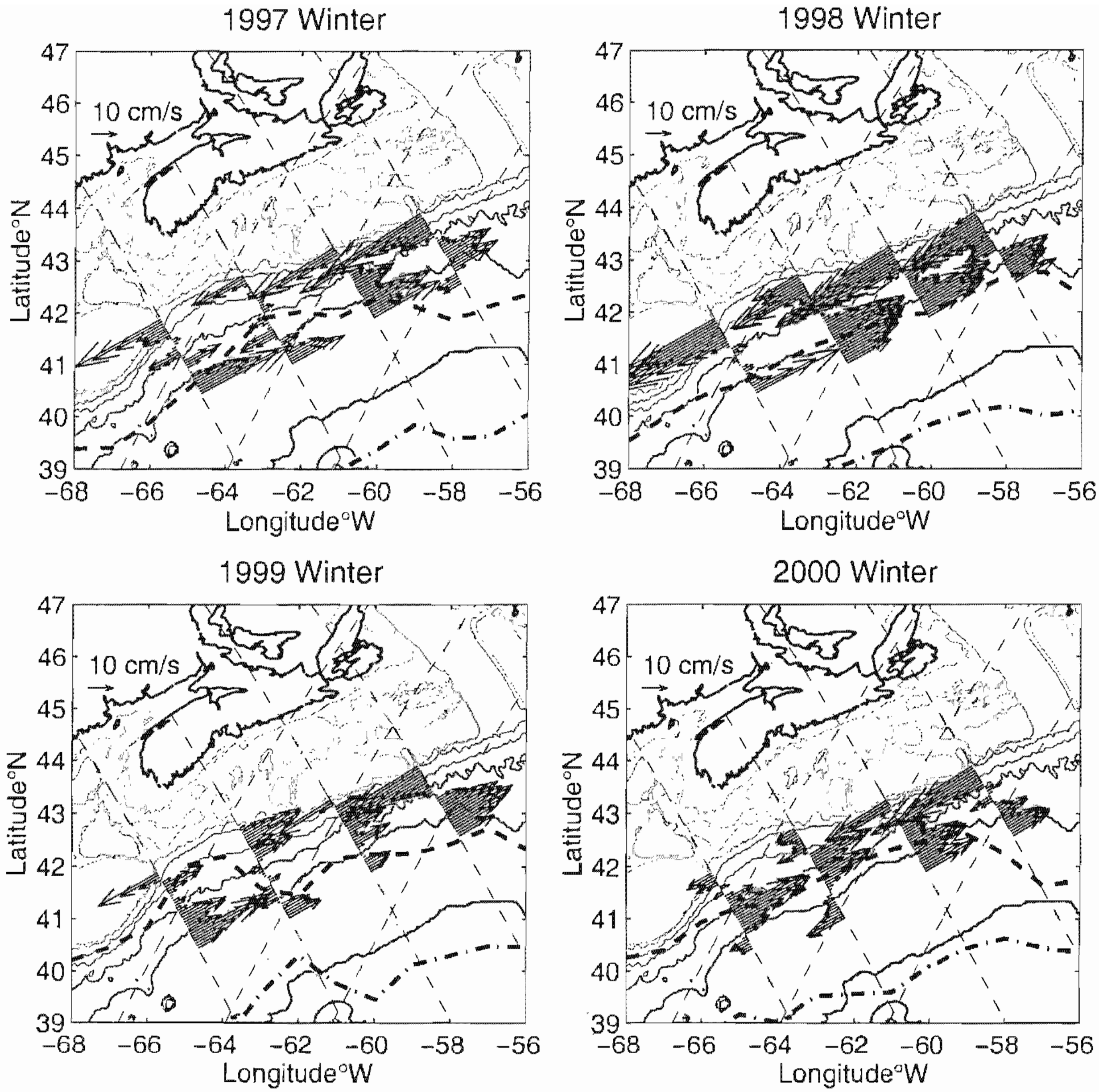


Figure 15 (continued).

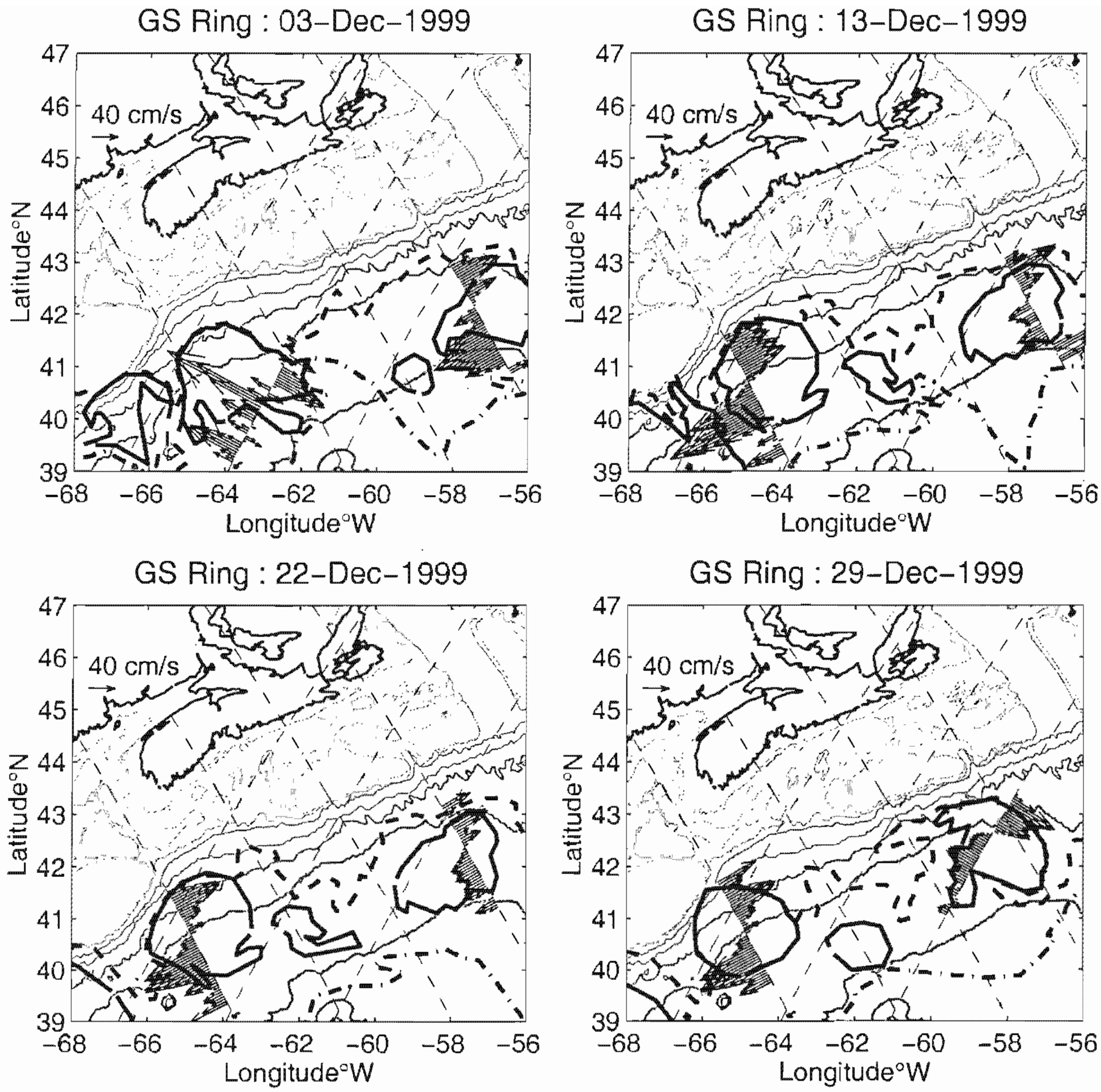


Figure 16. Frontal analysis data for December 1999, showing ring features (solid line) and the positions of the shelf/slope front (thick dashed lines) and the Gulf Stream northern boundary (dash-dotted lines) and selected altimetric current anomalies (arrows).

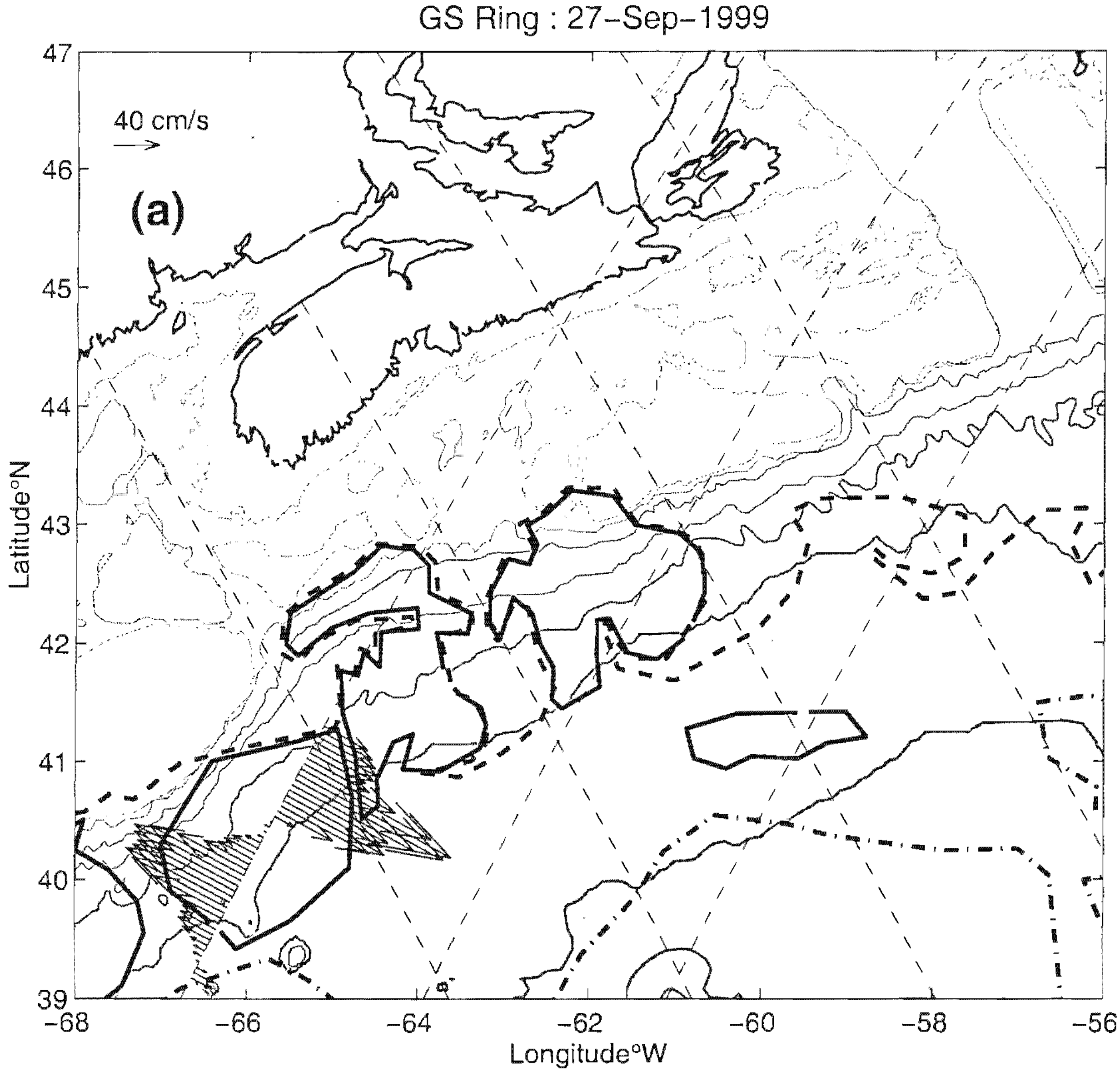


Figure 17. (a) Gulf Stream rings (solid lines) on Sept. 27, 1999 and altimetric cross-track current anomalies (arrows) on Track 071 on Sept. 30, 1999; (b) Comparison of the altimetric cross-track current anomalies and ADCP data (thick arrows). Also depicted are positions of the shelf/slope front (thick dashed lines) and the Gulf Stream northern boundary (dash-dotted lines).

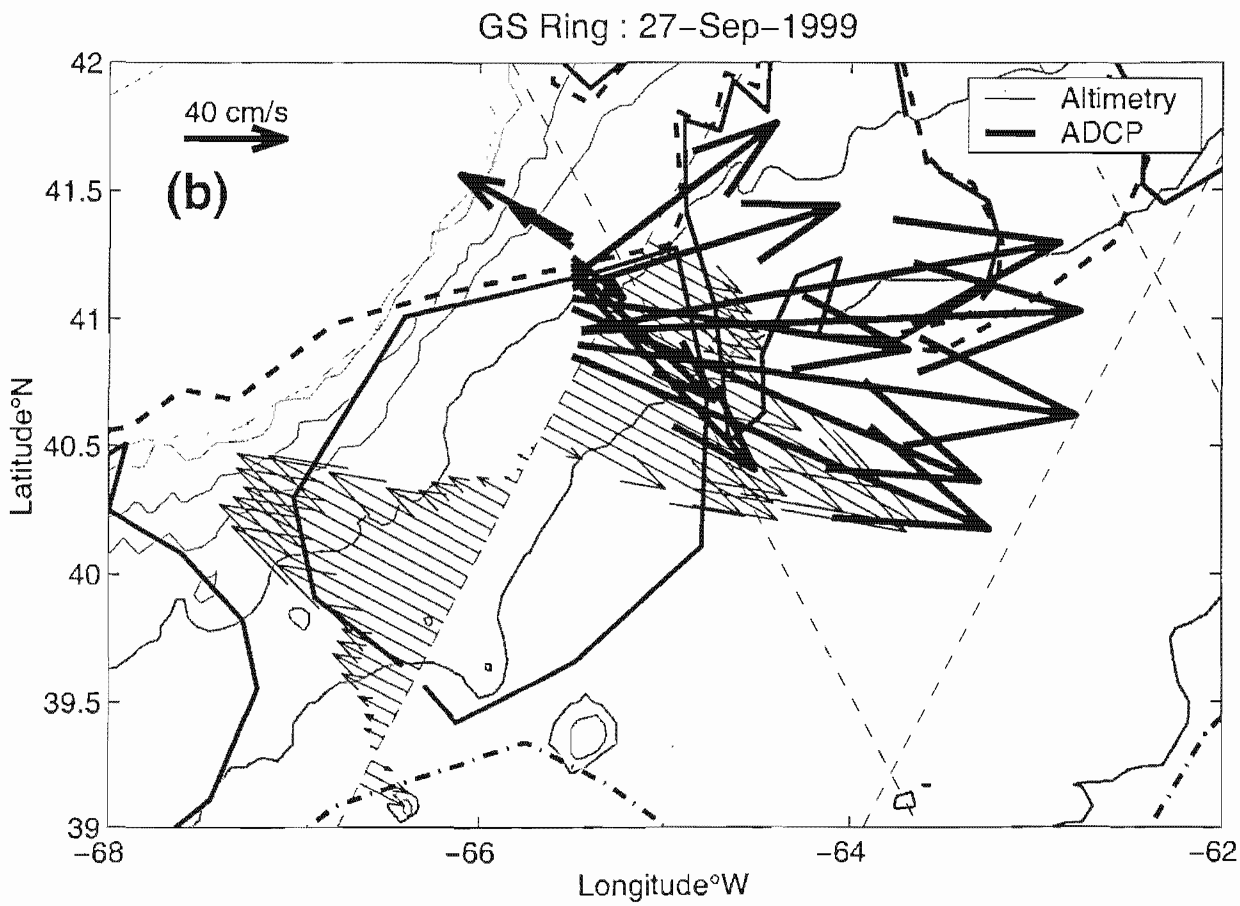


Figure 17 (continued).

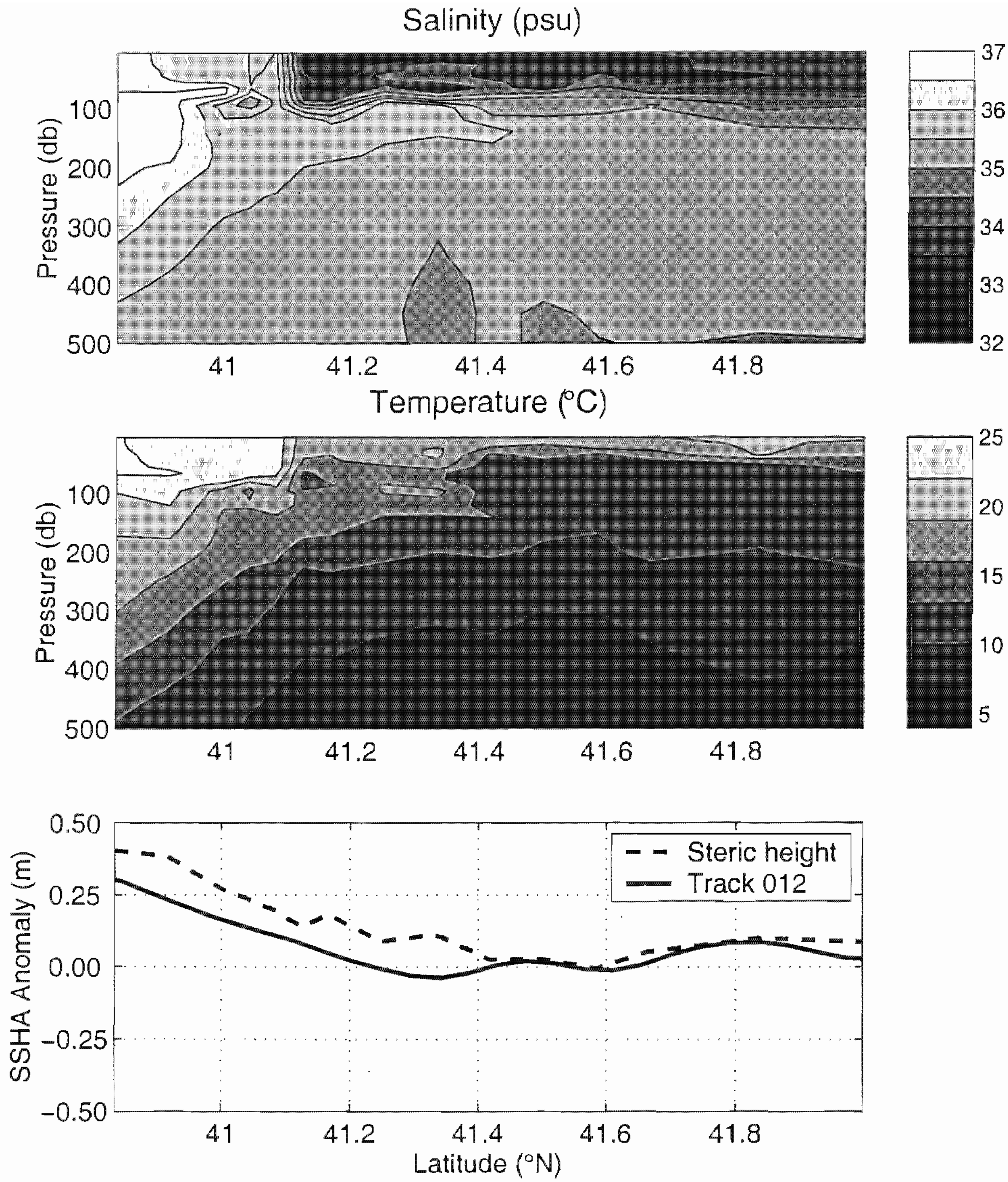
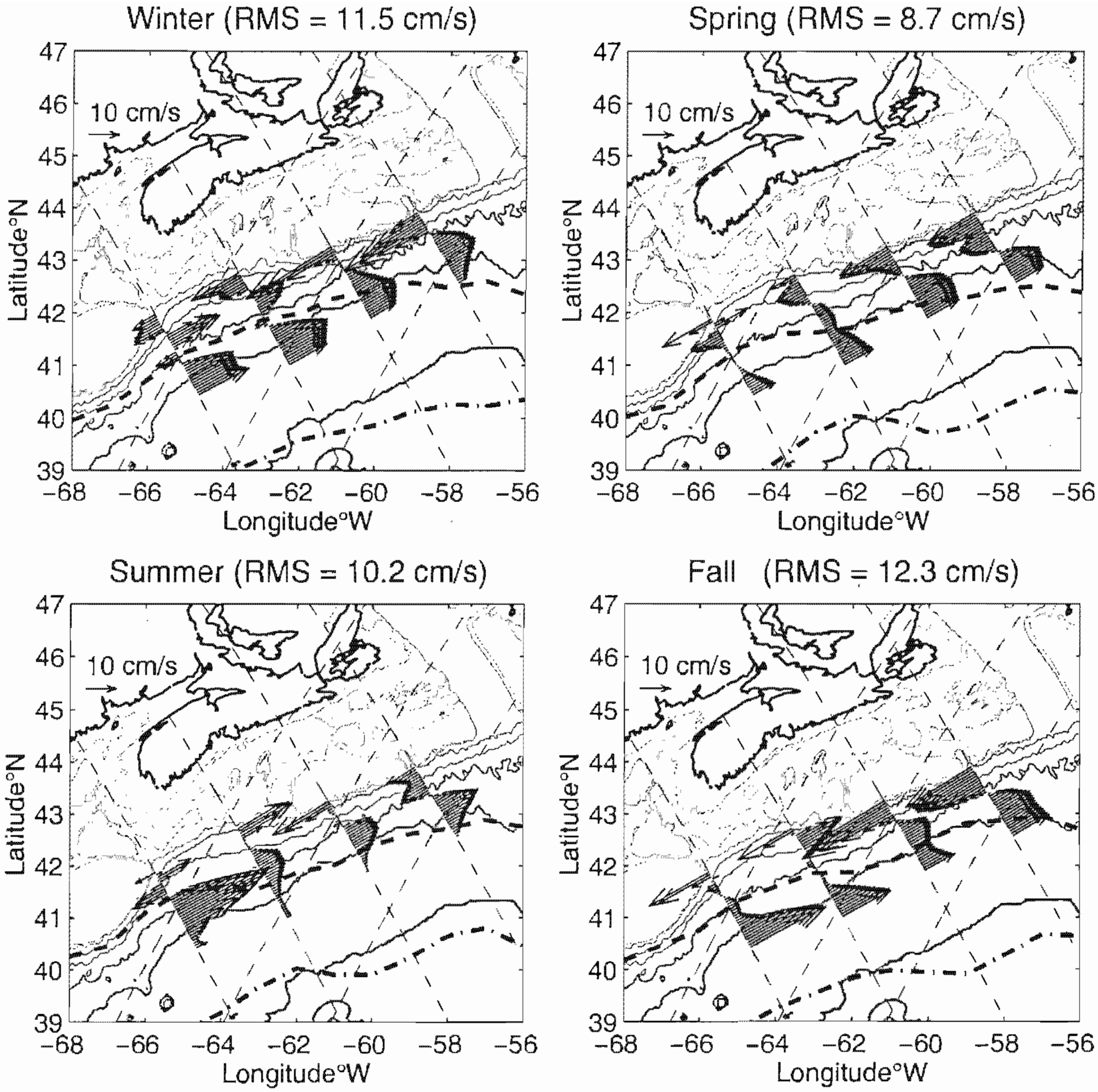
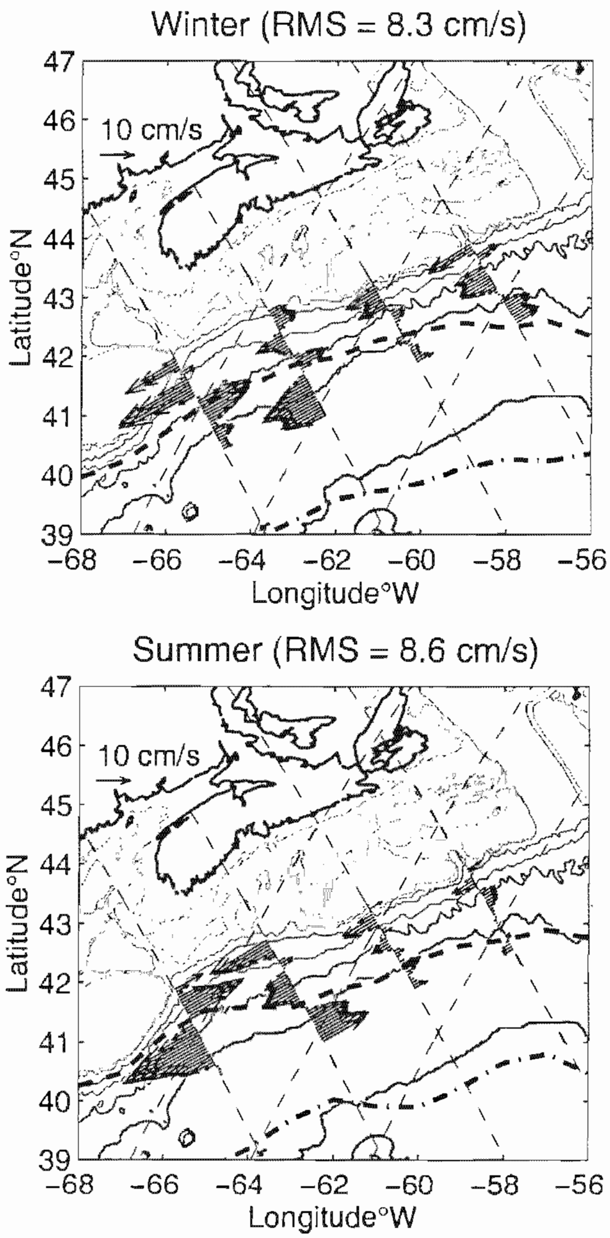


Figure 18. CTD temperature and salinity distribution across the ADCP section and Comparison of the steric height relative to the 500db and the T/P sea level anomalies on Track 12. See Fig.1 for location.



(a)

Figure 19. (a) Climatological seasonal-mean current anomalies in winter, spring, summer and fall over the Scotian Slope from Han et al.'s (1997) model solutions. (b) The altimetry-minus-model differences are for the four seasons. Also depicted are positions of the shelf/slope front (thick dashed lines) and the Gulf Stream northern boundary (dash-dotted lines) for each season.



(b)

Figure 19 (continued).

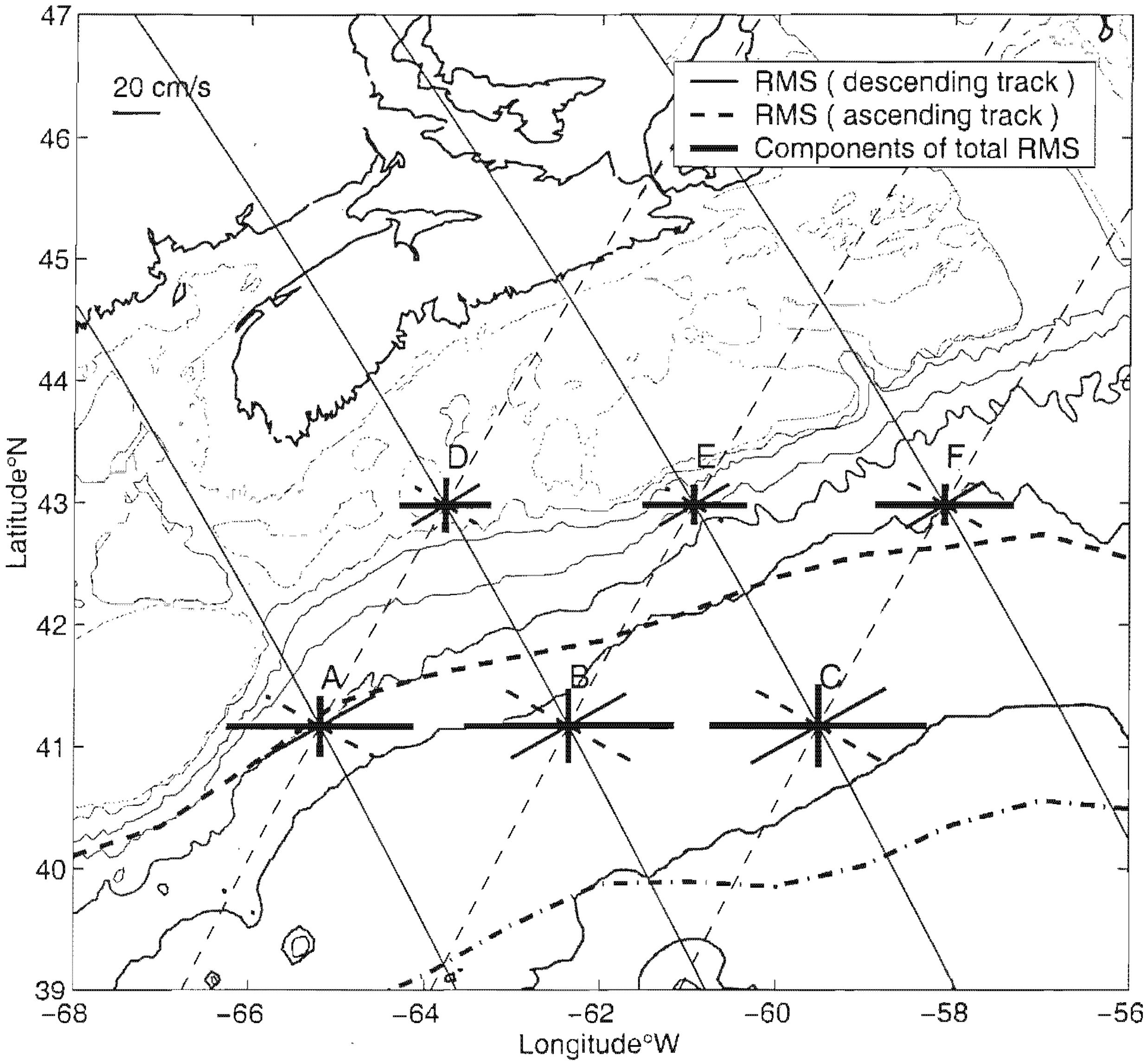


Figure 20. Altimetric current variability at crossovers, shown as twice the rms values. Also depicted are positions of the shelf/slope front (thick dashed lines) and the Gulf Stream northern boundary (dash-dotted lines) for the study period.