SEA SURFACE HEIGHT AND CURRENT VARIABILITY ON THE NEWFOUNDLAND SLOPE FROM TOPEX/POSEIDON ALTIMETRY

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ABSTRACT

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Nearly 10 years of TOPEX/Poseidon (T/P) sea level data (1992-2002) are analysed to explore sea level and current variability over the Newfoundland Slope. Sea level anomalies relative to local means for the period are derived and surface current anomalies normal to ground tracks are then calculated from the sea level anomalies under the geostrophic approximation. Climatological annual-mean surface currents normal to the ground tracks are also obtained from the solution of a regional circulation model. The sum of the model means and altimetric current anomalies is used to nominally represent absolute currents. Statistical analyses are carried out based on topographic regimes for along-slope and cross-slope current variability. The altimetric sea level and current variability increases offshore, toward the Gulf Stream or its extension the North Atlantic Current. Typical cross-track current variability is 10-20 cm/s over the SW and NE Slopes and 20-30 cm/s over the SE Slope. The total current variability may be estimated by a factor of 1.5 from the cross-track current variability of either the descending or ascending tracks. On average the variance is isotropic to within 21%. The sea level was higher in summer and lower in winter, with an increased range offshore. The shelf edge current (water depth of 200-3000 m) was stronger in fall and weaker in spring. The seasonal range was up to 10-20 cm/s. Interannual sea level and current variations were also substantial. The sea level over the southwestern (SW) Newfoundland Slope had a fall from 1994 to 1996 and a rebound after 1997, more significant towards the deep sea. The northeastern (NE) slope featured a sea level rise on the lower slope. Patterns over the southeastern (SE) slope appear to in between those of the SW and NE slopes. The Labrador Current over the slope (water depth of 200-3000m) seemed to be strongest in 1996-97.

RÉSUMÉ

G. Han and J. Li. 2004. Sea Surface Height and Current Variability on the Newfoundland Slope from TOPEX/Poseidon Altimetry. Can. Tech. Rep. Hydrogr. Ocean Sci. 234: viii + 40 p.

Des données TOPEX/Poseidon (T/P) sur le niveau de la mer recueillies sur un intervalle de près de dix ans (1992 à 2002) sont analysées à des fins d'exploration de la variabilité du niveau de la mer et des courants sur le talus continental terre-neuvien. Des anomalies du niveau de la mer par rapport aux moyennes locales pour la période sont dérivées et des anomalies des courants de surface perpendiculaires à la trajectoire sur le fond sont ensuite calculées d'après les anomalies du niveau de la mer en approximation géostrophique. Les courants de surface climatologiques annuels moyens perpendiculaires à la trajectoire sur le fond sont également dérivés de la solution offerte par un modèle de la circulation régionale. Les sommes des anomalies moyennes du modèle et des anomalies dérivées des données altimétriques sur les courants sont utilisées pour représenter de manière nominale les courants absolus. Des analyses statistiques basées sur les régimes topographiques pour la variabilité des courants parallèles et

perpendiculaires au talus sont effectuées. La variabilité altimétrique du niveau de la mer et des courants augmente en direction du large, vers le Gulf Stream ou son prolongement, le courant de l'Atlantique Nord. La variabilité caractéristique du courant perpendiculaire à la trajectoire est de 10 à 20 cm/s sur le talus S.-O. et le talus N.-E. et de 20 à 30 cm/s sur le talus S.-E. La variabilité totale du courant peut être estimée à 1,5 fois la variabilité du courant perpendiculaire à la trajectoire et ce d'après les passages descendants ou les passages ascendants. En moyenne la variance est isotrope à moins de 21 %. Le niveau de la mer est plus élevé en été et moins élevé en hiver, les différences étant accrues au large. Le courant en bordure de la plate-forme (profondeurs de 200 à 3000 m) est plus fort en automne et plus faible au printemps. La plage des valeurs saisonnières peut atteindre de 10 à 20 cm/s. Les variations d'une année à l'autre du niveau de la mer et des courants sont également substantielles. Le niveau de la mer sur la partie sud-ouest (S.-O.) du talus terre-neuvien a baissé de 1994 à 1996, puis il a remonté après 1997, de manière plus importante en direction de la haute mer. Une élévation du niveau de la mer a été observée sur la partie inférieure du talus N.-E. Les configurations sur le talus sud-est (S.-E.) semblent se situer entre celles observées sur le talus S.-O. et le talus N.-E. Le courant du Labrador sur le talus (profondeurs de 200 à 3000 m) semblait être le plus fort en 1996-1997.

1. Introduction

Ocean currents on the Newfoundland Slope (Fig. 1) south, east and north of the Grand Banks of Newfoundland are highly variable because of influences of the intense western boundary currents in the NW Atlantic Ocean (the relatively cold and fresh equatorward Labrador Current, and the warmer and saltier poleward North Atlantic Current), strong atmospheric forcing, and large inflows of sea ice (e.g. Loder et al, 1998). In addition to variations of the Labrador Current strength and pathway, meanders and eddies pinched from the North Atlantic Current can generate prominent temporal and spatial variability in regional hydrography and circulation, resulting in important shelf/deep-ocean interactions.

Most of the shelf-edge Labrador Current flows onto the northeastern Newfoundland Slope and continues southward through the Flemish Pass and toward the Tail of the Grand Bank. Some of the shelf-edge current flows around the Tail of the Bank and along the southern Newfoundland Slope, while some turns offshore into the Newfoundland Basin (Petrie and Anderson, 1983). An eastward branch north of Flemish Cap has also been identified but is poorly understood (Loder et al., 1998).

The Offshore Environmental Factors and the Climate Change Impacts on the Energy Sector subprograms of the federal Program on Energy Research and Development (PERD) have initiated studies of both short- and longer-term current variability in the Flemish Pass region. *In situ* moored measurements since 2002 and numerical modeling are important components. But moored measurements are expensive and have limited spatial coverage, and moorings on the Newfoundland Slope are vulnerable to heavy fishing activity and seasonal sea ice. Numerical models can be sensitive to parameterizations and representations of important dynamics, and are limited by data input for initialization, forcing and validation/constraint. On the other hand, satellite altimetry provides long-term and broad-scale synoptic measurements of instantaneous sea surface height (and slope) relative to a reference surface. Previous studies have clearly demonstrated the ability of T/P altimeter data to quantify current variability and understand dynamics over the Scotian Slope (e.g. Han, 2002a,b), and in the Labrador Sea (Han and Tang, 1999; 2001). A novel component in the present DFO/PERD studies is conducting similar analyses of satellite altimetry data for the Newfoundland Slope with a focus on the Flemish Pass and its vicinity.

The primary purpose of this study is to use T/P satellite altimeter data to estimate the spatial variability of surface current anomaly statistics for the Newfoundland Slope. In conjunction with numerical model results, this report describes current statistics and discusses major flow features. Knowledge of currents and their variability is particularly important for seismic surveys and drilling activities in the deep waters of the Newfoundland Slope, and is useful for complementing *in situ* measurements and ocean modeling for understanding circulation dynamics, and identifying the implications of climate variability and change.

In section 2 the techniques used to process and analyse the T/P data and to produce current anomaly estimates are briefly described. Section 3 presents current 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.

2. Methodology

2.1 T/P Altimeter Data

We used T/P sea-surface height data for the period from mid 1992 to early 2002, obtained from the NASA Pathfinder Project. T/P ground tracks were selected across the Newfoundland Slope and Rise south and east Newfoundland (Fig. 1). The satellite has a nominal repeat cycle of 10 days, so ideally there are 360 observations at each location. There are ascending (SW to NE) and descending (NW to SE) tracks with spacing of about 200 km in the study region, and 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.

A global ocean tide model (Ray, 1999) was used to remove oceanic and load tides. The remaining tide variations over the Newfoundland Shelf were estimated to have amplitude of 1 cm for M2 and K1 with apparent periods of 62 and 173 days, respectively (Han et al., 2002).

The NE Newfoundland Shelf and Slope and the Grand Bank were covered with pack ice in winter, resulting in missing data points. The regional ice conditions changed from winter to winter significantly in the 1990s. It has been found that the impacts of the ice related data loss are minor on the major results of this study.

An along-track Butterworth digital filter with a filter width of 46 km was applied to the sea surface height (SSH) to reduce noise influences on the current estimates. The results presented are based on the smoothed height data unless indicated otherwise. A time-mean sea surface was constructed from T/P data. We then calculated the SSH anomalies relative to the mean sea surface (MSS). Both the marine geoid and mean oceanic topography are removed by this procedure. The sea surface height anomalies on Track 096 on February 24, 1998 are shown in Fig. 2. A crossover analysis indicates that the instantaneous SSH anomalies have a root mean square (rms) error of ~2 cm.

2.2 Derivation of Sea Surface Current Anomalies

From the T/P sea surface height (SSH) anomalies, geostrophic surface current anomalies perpendicular to the track (e.g. Fig. 2, positive westward) were derived. The estimated geostrophci current anomalies have an rms error of ~4 cm/s. 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 anomalies derived from the anomalies of sea surface slope.

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 annual-mean currents from Han's (2003) model solutions. The model surface currents were interpolated onto the satellite ground tracks. The components normal to the track were then derived. We can see an equatorward flow along the shelf edge and the upper continental slope, and a poleward current along the lower continental slope (Fig. 3). Although the model produces the Labrador Current transport consistent with observational estimates from moored measurements through the Flemish Pass, a detailed evaluation of the model currents against current meter data has not been conducted. Therefore, the focus here is on the current anomalies rather than the absolute currents.

The crossover points of the descending and ascending tracks are the only locations that allow us to estimate the total (both directional components) current anomalies from altimetry. We have interpolated spatially and temporally geostrophic current anomalies normal to descending and ascending tracks to generate time series of the total current anomalies at the crossover points. The normal-to-track components are then transformed into the along- and cross-isobath components. Fig. 4 shows the two current components at crossovers I and D.

3. Results

3a. Statistics of Variability

The SSH anomalies on Track 096 (Fig. 2) show substantial along-track variations, ~5 cm over the shelf, ~10 cm over the slope and ~ 50 cm associated with the Gulf Stream. The associated current anomalies (normal component) have magnitudes of 10-20 cm/s over most of the shelf, ~ 50 cm/s over the slope and ~100 cm/s in the Gulf Stream. There are significant variations at various time scales in the current anomalies, as seen in time series of the anomalies (Fig. 4) at crossovers I (water depth of about 200 m) and D (water depth of about 1000 m). The predominant slope current anomalies in Figure 2 have cross-slope scales of 50-100 km which are consistent with cross-slope shifts of the shelf-edge Labrador Current which has a width of this order (e.g. Hannah et al. 1995).

Fig. 5 shows the rms values of the altimetric SSH anomalies. There is generally increased variability as one proceeds offshore towards the Gulf Stream and the North Atlantic Current. Typical values are 5-10 cm over the upper slope and 10-15 cm over the lower slope. There is also a weaker amplification over the shallower shelf areas such as the Grand Banks.

Fig. 6 shows the spatial distribution of rms variability of the cross-track currents. The variability increases offshore. Typical values are 10-20 cm/s over the SW and NE Slopes and 20-30 cm/s over the SE Slope. Differences between the upper (200-1000m) and lower (1000-3000m) slope are not significant for the northeastern Newfoundland Slope. There is a suggestion of a weak secondary maximum in rms currents over the upper slope, and a clear indication of a maximum between the upper and lower slope south of Grand Bank, which may reflect variability in Labrador Current.

To provide further statistical information on the along-slope and cross-slope structure of the current anomalies, four along-track bands were selected based on bathymetry: (i) 200-1000m, (ii) 1000-3000m, and (iii) 3000-4000m (continental rise) and (iv) 4000-4500m. Fig. 7, 8, and 9 shows the rms values of the altimetric current anomalies for the four bands and Tables 1-3 summarise exceedance percentages of current anomalies. The rms values for the four bands for each track also demonstrate significant contrast in anomaly strength between the slope currents over the upper and lower slope and the Gulf Stream and North Atlantic Current in the deep ocean. However, the contrast between the upper and lower slope is more sophisticated. It appears that for the SW and SE Grand Bank tracks, the occurrence of currents in excess of 0.5 m/s over the lower slope is about twice that over the upper slope, but different pattern off the NE Grand Bank where GS or NAC interaction does not exist. The current variability over the lower slope is largest off the SE Grand Bank, intermediate off the SW Grand Bank and tracks just north of Flemish Cap (058, 096), and smallest further north of the NE Newfoundland Slope. The shelf edge Labrador Current has largest rms variability on the SE Newfoundland Slope near the Tail of the Grand Bank.

T/P data at crossovers of descending and ascending tracks allow us to estimate total rms values of current anomalies at those locations (Fig. 6b). We have interpolated spatially and temporally cross-track geostrophic current anomalies to generate time series at crossovers. The normal-to-track components are then transformed into the eastward and northward components. The total rms current value is the square root of the sum of the mean square values. We have also calculated the ratio of the rms variability for the total current to that for the cross-track components (Table 4). On average, there appears no systematic difference in ratios between the descending and ascending tracks. The total current variability over the Newfoundland Slope may be estimated by a factor of 1.5 from the cross-track current variability of either the descending or ascending tracks.

From the eastward and northward current components, we have derived major and minor axes, angle of the major axis, and ratio of the minor to major axes. The ratios vary from 0.29 to 0.79 with an average of 0.46 (Table 4). On average, the variance of T/P altimetric current anomalies is isotropic to within 21% over the Newfoundland Slope. The variance seems to be more isotropic over the NE Newfoundland Slope (also Fig. 6b). The dominant direction of variance near the 4000-m isobath south of the Grand Bank is in the east-west direction. Over the Newfoundland Slope inshore of the 3000-m isobath, the major axis tends to be in the along-isobath direction.

3b. Seasonal and Interannual Variability

The T/P SSH anomalies at each location are averaged over all years by month plotted in the month-latitude domain for selected track segments (Fig. 10). There are large seasonal changes, with sea level generally higher in spring-summer and lower in winter-fall. The magnitude of the changes generally increases offshore, especially over the SW and SE Newfoundland Slope. There are differences in different regions, large variability in the SW region and small in the NE region. Typical ranges are 10, 20 and 30 cm for the upper slope, lower slope and further offshore over the SW and SE Newfoundland Slope. While over the NE Newfoundland Slope, the cross-slope variability is much smaller. The seasonal cycle may be associated with the thermal expansion and contraction as a result of solar heating and cooling, fluctuations of core signature of the slope water currents, and meandering and frontal eddies from the Gulf Stream and the North Atlantic Current. Since the magnitudes are largest in deep water and the seasonal changes are not smooth or spatially coherent, the seasonal cycle in deep water may in part be a result of aliasing of shorter-term eddy variability.

Altimetric seasonal-mean current anomalies (Jan-Mar, Apr-Jun, Jul-Sep, and Oct-Dec for winter, spring, summer and fall respectively) were calculated from the T/P current anomaly data. Seasonal-mean current fields (Fig. 11) were then constructed by adding the model mean flows derived from Han (2003) to the altimetric seasonal-mean anomalies. The equatorward shelf edge current is stronger in fall/winter and weaker in spring/summer. The seasonal ranges are typically 5-10 cm/s, and can reach up to 10-20 cm/s (e.g. on track 024). Overall, the seasonal variation in shelf-edge Labrador Current is weak compared with its mean, which is consistent with previous diagnostic model results (Hannah et al., 1995). The seasonality in the poleward current along the 4000-m isobath is also indicated. The current seems stronger in summer and fall and weaker in winter and spring in the SW and SE regions.

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

Over the SW Newfoundland Slope and Rise, the sea level variation had a pronounced interannual cycle, with an increasing magnitude towards the south (Fig. 12). Sea level variations showed a significant fall from 1994 to 1996, with a rapid rebound after 1997. The sea level range amounts to 10-20 cm. Over the shelf edge and upper continental slope between the 200- and 1000-m isobaths, the sea level variability is much less. The NE slope clearly shows a sea level rise on the lower slope over the period, with weak oscillations at higher frequencies. Features over the SE slope appear to in between those of the SW and NE slope. Offshore (3000-4000m) SE band has reduced coherence across tracks than others, perhaps reflecting greater eddy influence.

A time-latitude distribution of seasonal-mean sea levels on Track 096 is shown in Fig. 13. The results indicate the differences among the SW slope, the Grand Bank and the NE Slope. The offshore variability is dominated by eddies or meanders rather than a regular seasonal cycle, so that the apparent offshore climatological seasonal variation in Fig. 10 indeed reflects aliasing. There is a more regular annual variation on the Grand Bank and NE slope, although a lot of interannual variability (including little seasonal cycle in some years).

Monthly-mean unit-depth volume transport is calculated for segments based on bathymetry or latitude. After annual and semiannual cycles being removed, the monthly means are averaged to obtain seasonal means by season and year, which are then smoothed by five-point moving filter. There are significant interannual changes (Fig. 14) besides the seasonal change (also see Fig. 11) associated with the Labrador Current over the Newfoundland Slope. The surface Labrador Current appeared to be intensified on the NE and SE Newfoundland Slope in 1996/97 and on the SW Newfoundland Slope in 1997. The intensification is consistent with moored measurements of a stronger and colder westward shelf-edge current off St. Perrie Bank in 1997 (Smith, P.C., personal communication, 2000) and Han's (2002) finding of a Labrador Current pulse traveling through the Scotian Slope in 1997/1998.

As expected, the eastward transport north of the Flemish Cap is in positive correlation with the westward flow south of the Cap (Fig. 15), both representing the anticyclonic partial eddy around Flemish Cap. They were weaker in mid 1990s and stronger in early and late 1990s, nearly opposite to the Labrador Current. Presumably the Labrador Current bifurcates north of Flemish Pass, with one branch being the flow north of the Cap and the other through Flemish Pass. The dynamics underlying the opposite interannual cycles associated with the shelf-edge Labrador Current and the Flemish Cap anticyclonic flow is unclear.

4. Summary

We have used T/P altimeter data from 1992 to 2002 to study sea level and current variability over the Newfoundland Slope. The T/P results reveal strong sea level and surface current variability at various temporal and spatial scales.

The altimetric sea level variability increases offshore, toward the Gulf Stream or its extension the North Atlantic Current. The rms values for the four bands for each track also demonstrate significant contrast in anomaly strength between the slope currents over the upper and lower slope and the Gulf Stream and North Atlantic Current in the deep ocean. However, the contrast between the upper and lower slope is more sophisticated. It appears that for the SW and SE Grand Bank tracks, the occurrence of currents in excess of 0.5 m/s over the lower slope is about twice that over the upper slope, but different pattern on NE Grand Bank where GS or NAC interaction does not exist. The current variability over the lower slope is largest off the SE Grand Bank, intermediate off the SW Grand Bank and tracks just north of Flemish Cap (058, 096), and smallest further north of the NE Newfoundland Slope. The shelf-edge Labrador Current has largest rms variability on the SE Newfoundland Slope near the Tail of the Grand Bank. Typical cross-track current variability is 10-20 cm/s over the SW and NE Slopes and 20-30 cm/s over the SE Slope. The total current variability may be estimated by a factor of 1.5 from the cross-track current variability of either the descending or ascending tracks. On average the variance is isotropic to within 21%.

The sea level was higher in summer and lower in winter, with an increased range offshore. The shelf edge current (water depth of 200-3000 m) was stronger in fall and weaker in spring. The seasonal range amounts to 10-20 cm/s.

At the interannual scale, there were significant sea level and current variations. The sea level over the SW Newfoundland Slope had a fall from 1994 to 1996 and a rebound after 1997, more significant towards the deep sea. The NE Slope featured a sea level rise on the lower slope. Patterns over the SE slope appear to in between those of the SW and NE slope. The Labrador Current over the slope (water depth of 200-3000m) seemed to be strongest in 1996-97.

Acknowledgement

We thank J. Loder for helpful comments and suggestions. The project was funded through the Offshore Environmental Factors Program and the Climate Change Impacts on Energy Sector Program of the Federal Program for Energy, Research and Development (PERD), and Fisheries and Oceans Canada. T/P data were obtained from NASA Jet Propulsion Lab and Pathfinder Project.

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Table 1. Exceedance percentages of altimetric current anomalies over the SW Newfoundland Slope.

Depth (m)	Range (m/s)	Track 020 42.7-44.8N	Track 037 42.4-44.8N	Track 058 42.5-45.0N	Track 096 41.3-45.2N
200-1000	>0.25	2.6	9.1	4.7	16.9
	>0.50	0.0	0.1	0.0	1.7
	>1.00	0.0	0.0	0.0	0.0
1000-3000	>0.25	4.5	5.2	7.7	20.8
	>0.50	0.1	0.4	0.4	3.7
	>1.00	0.0	0.0	0.0	0.0
3000-4000	>0.25	11.3	8.6	9.7	22.5
	>0.50	0.3	0.4	1.9	3.7
	>1.00	0.0	0.0	0.0	0.0
4000-4500	>0.25	13.1	14.1	14.9	24.2
	>0.50	0.9	0.7	1.0	6.1
	>1.00	0.0	0.0	0.0	0.0

Table 2. Exceedance percentages of altimetric current anomalies over the SE Newfoundland Slope.

Depth (m)	Range (m/s)	Track 113 41.0-43.4N	Track 024 42.9-45.3N	Track 062 44.5-46.9N	Track 100 45.0-46.8N
200-1000	>0.25	23.2	10.3	7.2	9.1
	>0.50	2.6	0.0	0.2	0.3
	>1.00	0.0	0.0	0.0	0.0
1000-3000	>0.25	18.7	10.6	6.2	24.0
	>0.50	1.8	0.4	0.2	2.8
	>1.00	0.0	0.0	0.0	0.1
3000-4000	>0.25	37.3	31.4	19.1	38.1
	>0.50	8.4	7.5	2.1	7.2
	>1.00	0.3	0.2	0.0	0.1
4000-4500	>0.25	-	38.5	33.7	41.3
	>0.50	-	11.7	9.2	9.3
	>1.00	-	0.6	0.4	0.1

Table 3. Exceedance percentages of altimetric current anomalies over the NE Newfoundland Slope.

Depth (m)	Range (m/s)	Track 020 50.0-52.0N	Track 058 48.5-51.9N	Track 096 47.6-50.6N	Track 007 48.2-50.1N
200-1000	>0.25	2.4	6.4	5.8	1.9
	>0.50	0.0	0.2	0.0	0.1
	>1.00	0.0	0.0	0.0	0.0
1000-3000	>0.25	2.5	1.7	3.1	3.0
	>0.50	0.1	0.0	0.1	0.1
	>1.00	0.0	0.0	0.0	0.0
3000-4000	>0.25	16.2	4.9	10.7	28.6
	>0.50	2.3	0.1	0.9	4.9
	>1.00	0.0	0.0	0.0	0.0
4000-4500	>0.25	-	22.6	25.0	41.5
	>0.50	-	5.3	2.2	12.6
	>1.00	-	0.4	0.0	0.8

Table 4. The rms values (cm/s) at crossovers for the descending (d-rms) and ascending (a-rms) cross-track current anomalies and for the total (t-rms) current anomalies. The ratios of the latter to the former are presented as t/d and t/a for descending- and ascending tracks respectively. Also shown are major and minor axes (cm/s), angle of the major axis (degree, positive anticlockwise from the east), and ratio of the minor to major axes of T/P current anomalies at crossovers. SD: Standard deviation. The geographic locations of the crossovers (longitude and latitude, both in degrees) are given in brackets (also see Fig. 6b).

location	d-rms	a-rms	t-rms	t/d	t/a	angle	major	minor	ratio
A(-53.9,44.7)	8.5	9.3	13.4	1.59	1.44	-3.6	12.3	5.4	0.43
B(-52.4,43.0)	17.4	17.7	27.1	1.56	1.53	-0.8	25.6	8.9	0.35
C(-51.0,41.2)	35.1	37.9	54.9	1.56	1.45	-2.3	50.7	21.1	0.42
Q(-49.6,39.2)	44.1	44.7	68.2	1.54	1.52	0	64	23.5	0.37
D(-49.6,43.0)	22	13.1	28.2	1.28	2.15	11.1	27.1	8.1	0.3
E(-48.2,41.2)	28	42.1	55.7	1.99	1.32	-7.9	53.6	15.3	0.29
F(-48.2,44.7)	16.5	10.1	20.3	1.23	2.01	13.6	19	7.2	0.38
G(-46.8,43.0)	35.4	35.8	56.6	1.6	1.58	-0.5	54	17.3	0.32
H(-49.6,49.0)	8.1	10	12.5	1.53	1.25	-37.5	10	7.5	0.75
I(-48.2,47.7)	9.1	11.2	14.2	1.56	1.26	-11.8	12.1	7.3	0.6
J(-46.8,46.2)	13.8	7.6	16	1.16	2.11	20.1	14.8	6.2	0.42
K(-45.4,44.7)	26.5	25.6	40.1	1.51	1.57	0.4	37.6	14	0.37
L(-49.6,51.4)	6.4	9.1	10.9	1.71	1.21	-35.3	9	6.3	0.7
M(-48.2,50.3)	6.6	7.9	10.1	1.53	1.27	-39.8	7.9	6.2	0.79
N(-46.8,49.0)	8.1	7.8	11.6	1.44	1.49	1.5	10.1	5.8	0.58
O(-45.3,47.7)	8.3	7.1	11.1	1.34	1.55	11.2	9.5	5.7	0.6
P(-43.9,46.2)	23	24.6	36.2	1.57	1.47	-2.3	33.9	13.1	0.39
R(-56.7,44.7)	15.3	9.3	17.8	1.16	1.92	20.1	16.1	7.8	0.48
S(-55.3,43.0)	17.2	16.1	25.6	1.49	1.59	1.3	24	9.1	0.38
T(-53.9,41.2)	30.5	32.1	49.1	1.61	1.53	-2.2	46.5	15.8	0.34
U(-52.4,39.2)	55.3	41.5	74.2	1.34	1.79	8.5	69.7	26	0.37
Mean				1.49	1.57				0.46
SD				0.19	0.28				0.15
Min				1.16	1.21				0.29
Max				1.99	2.15				0.79

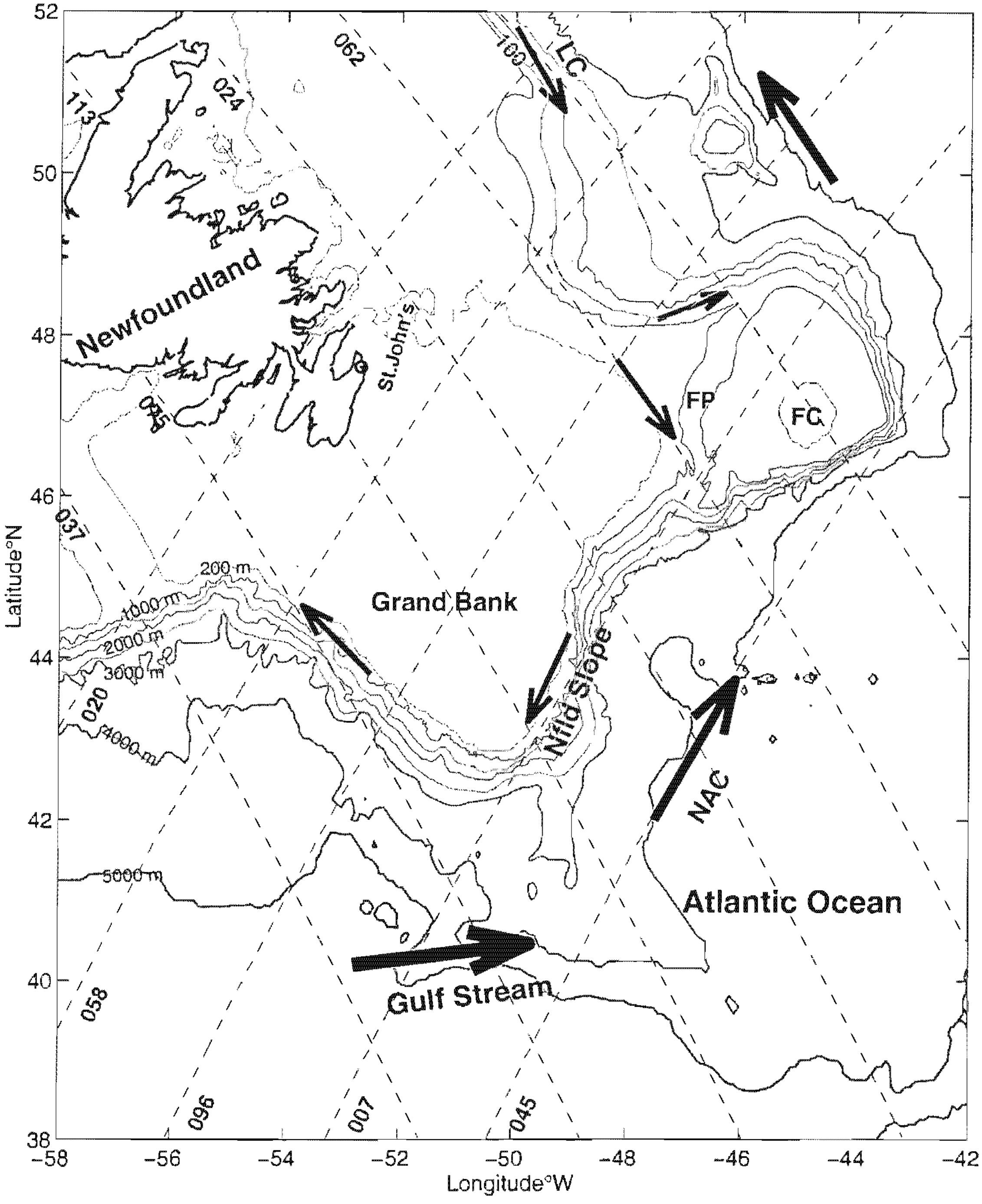


Figure 1. Map showing the Newfoundland Slope, and adjacent shelf and deep oceans. The labeled (the numerical label is the track number) dashed lines are the selected T/P ground tracks on which the analysis is performed. FP: Flemish Pass; FC: Flemish Cap; NAC: North Atlantic Current; LC: Labrador Current.

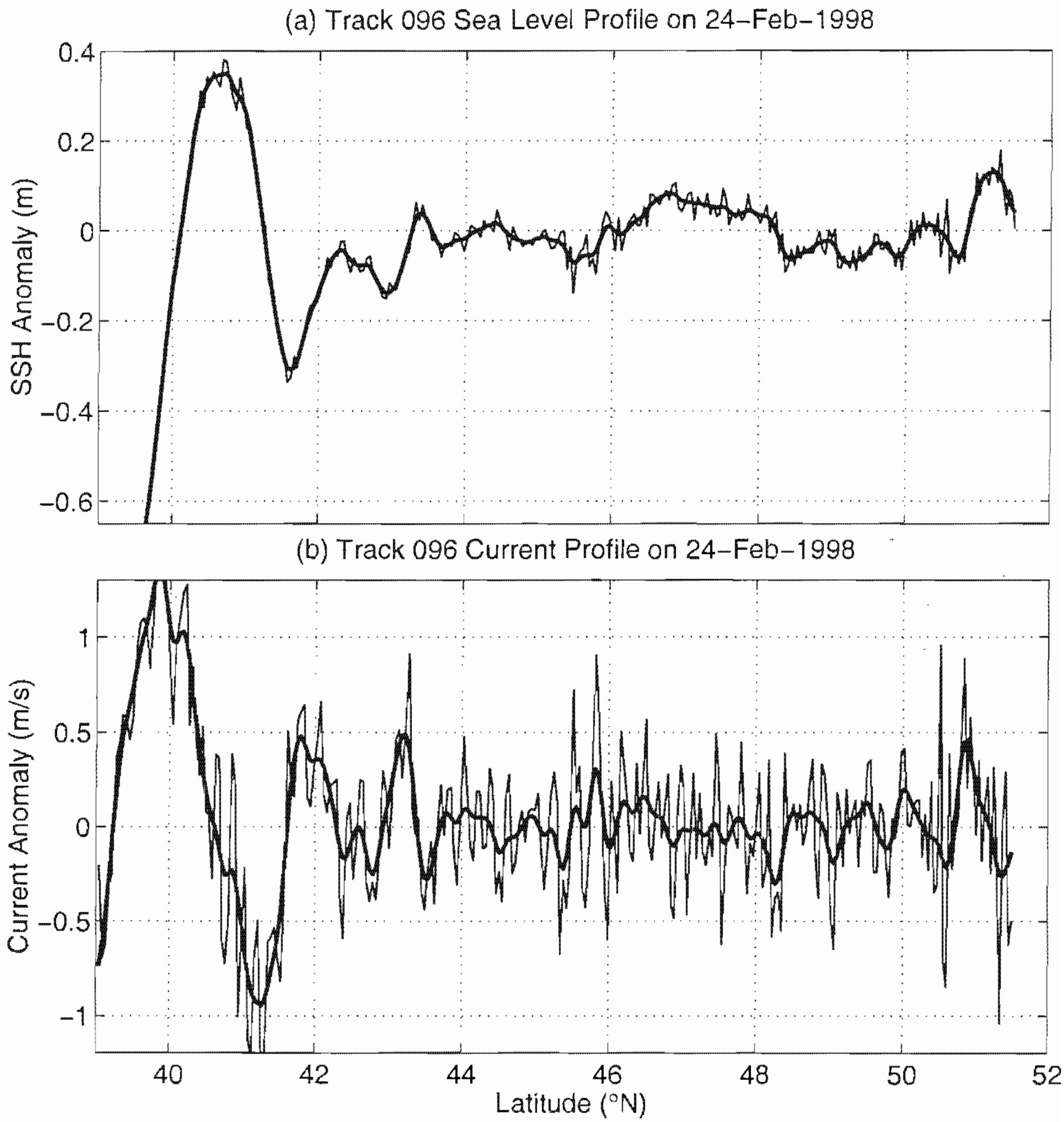


Figure 2. Along-track profiles of sea level and geostrophic surface current anomalies (positive westward) normal to the track for track 096 extending from the SW Grand Bank to the NE Newfoundland Slope, on February 24, 1998. Smoothed (thick line) and unsmoothed (thin line).

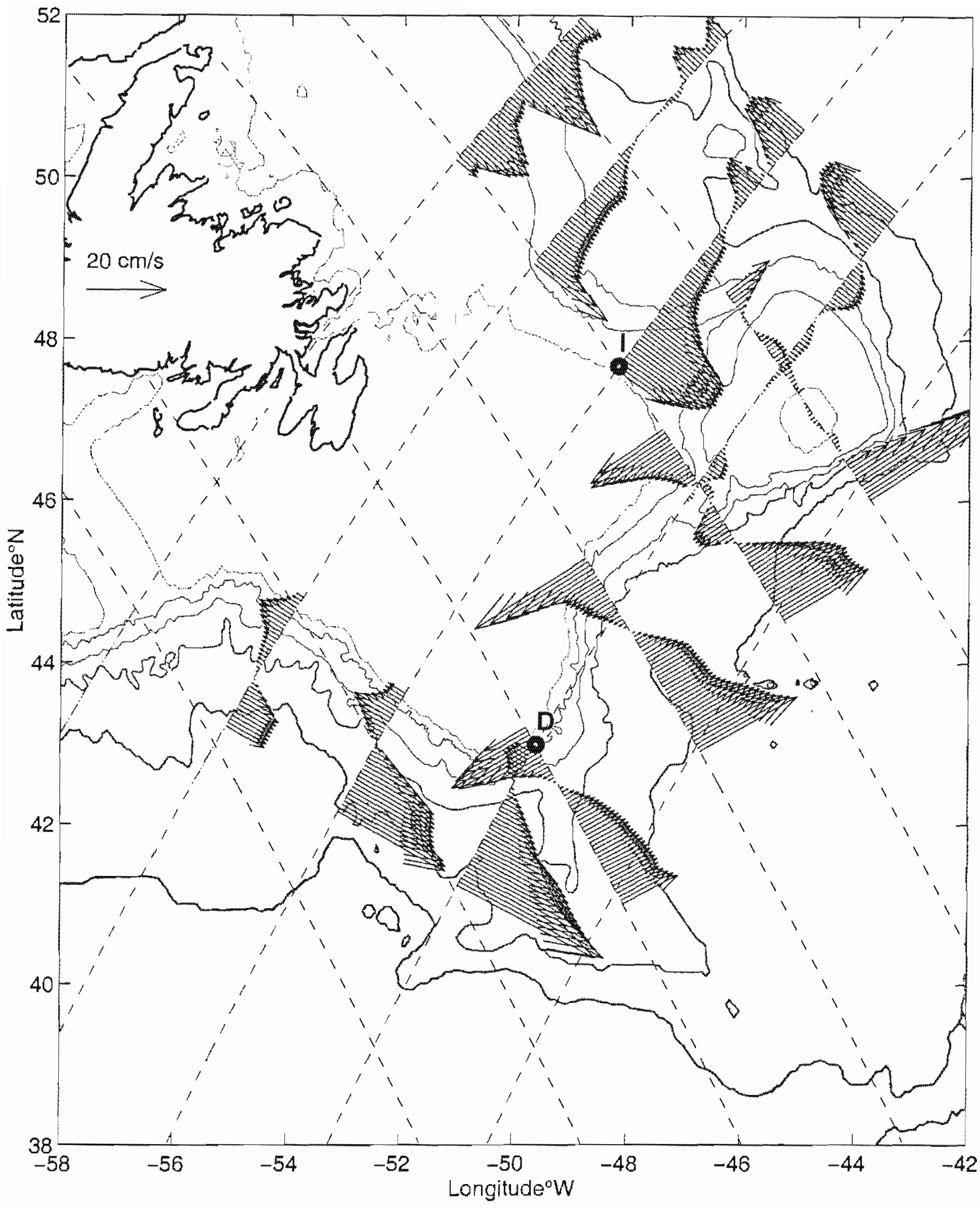


Figure 3. Climatological annual-mean surface currents over the Newfoundland Slope derived from Han (2003) model results. Only cross-track components are shown.

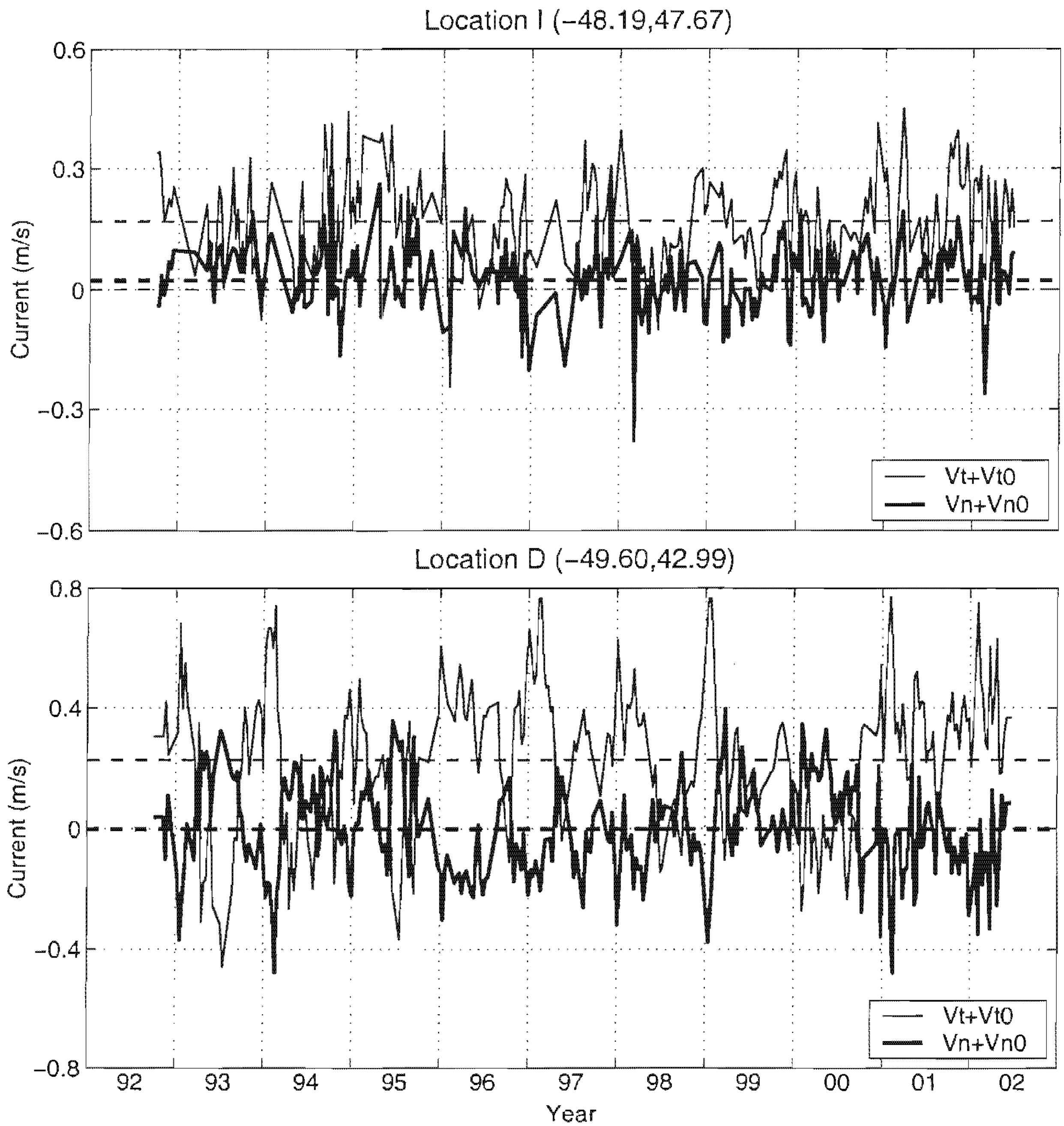


Figure 4. Time series of along-isobath (thin line) and cross-isobath (thick line) currents at crossovers I and D on the northeast and southeast upper slopes of the Grand Bank, respectively. See Fig.3 for exact locations. The currents are constructed from T/P current anomalies and Han's (2003) model solutions (dashed lines).

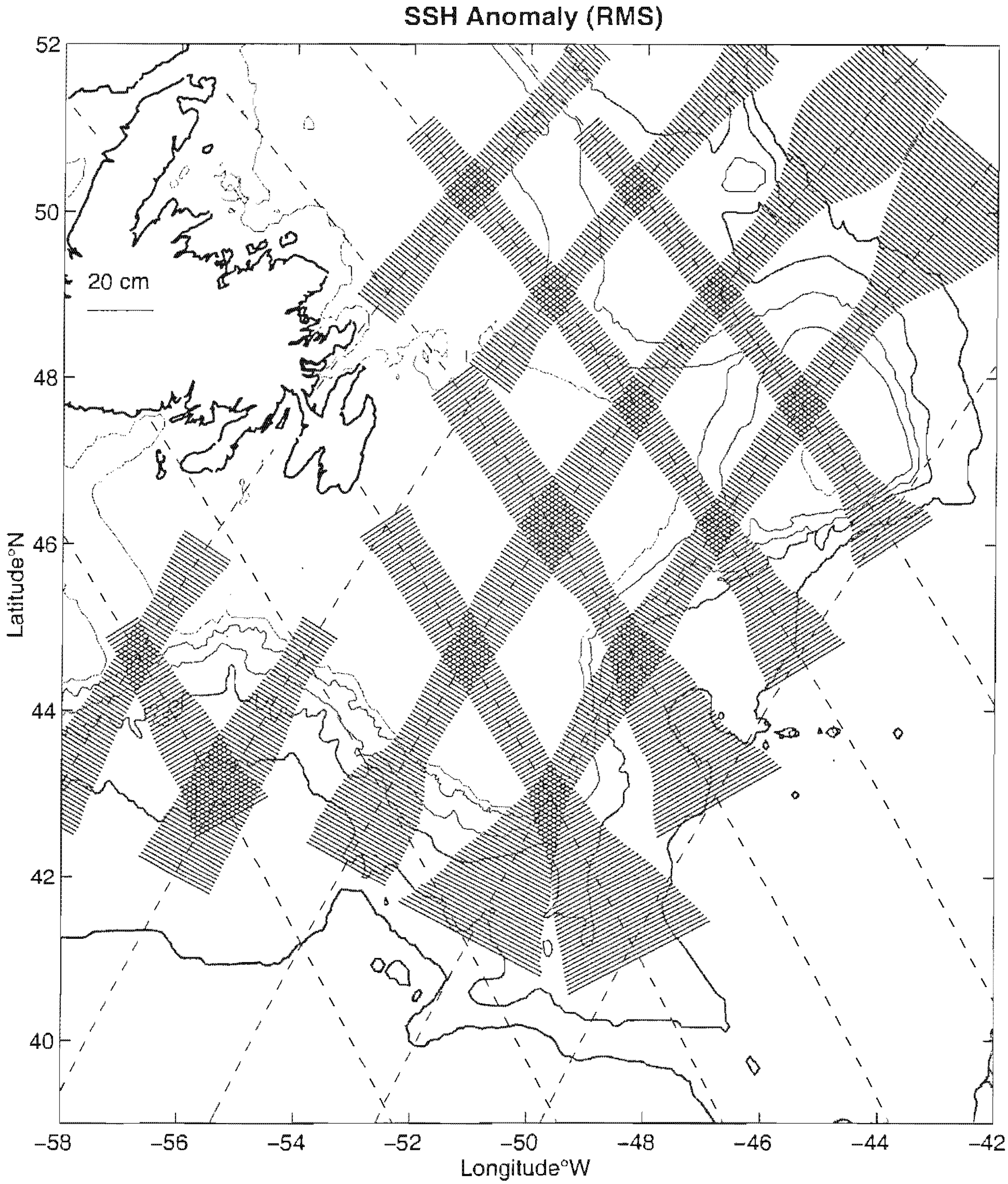
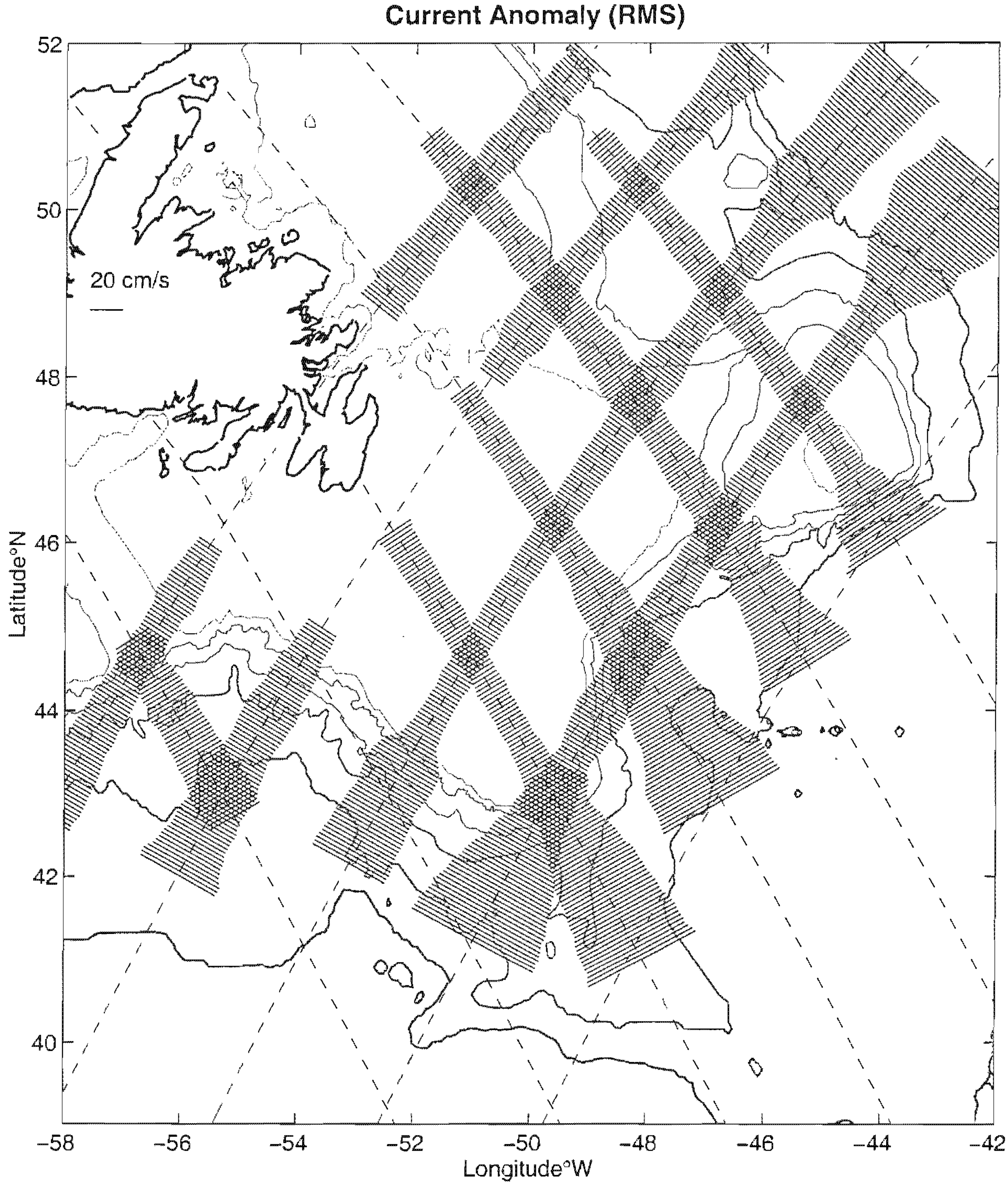
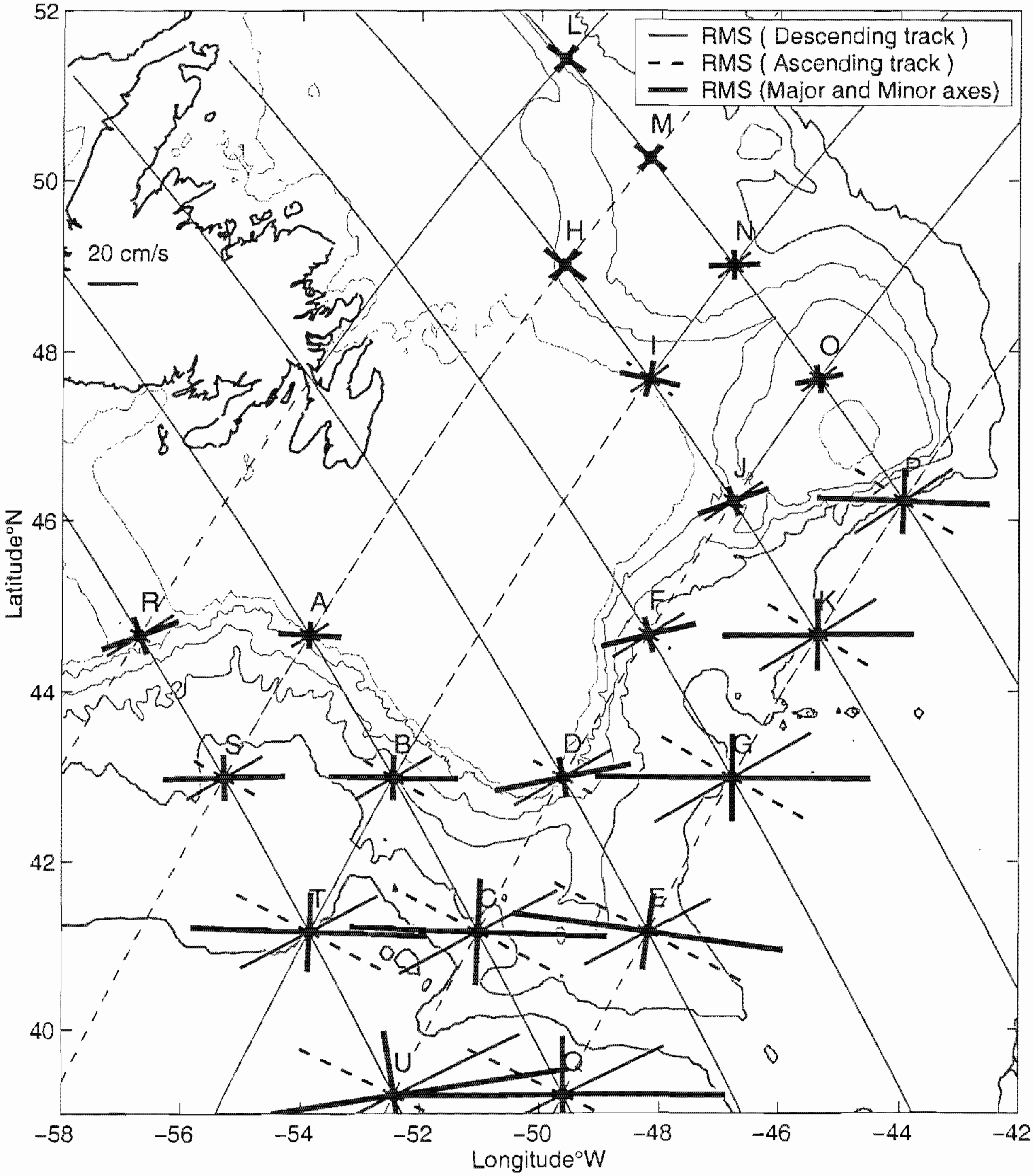


Figure 5. Sea level variability over the Newfoundland Slope calculated from the T/P altimetry data from 1992 to 2002 and plotted as twice the rms values.



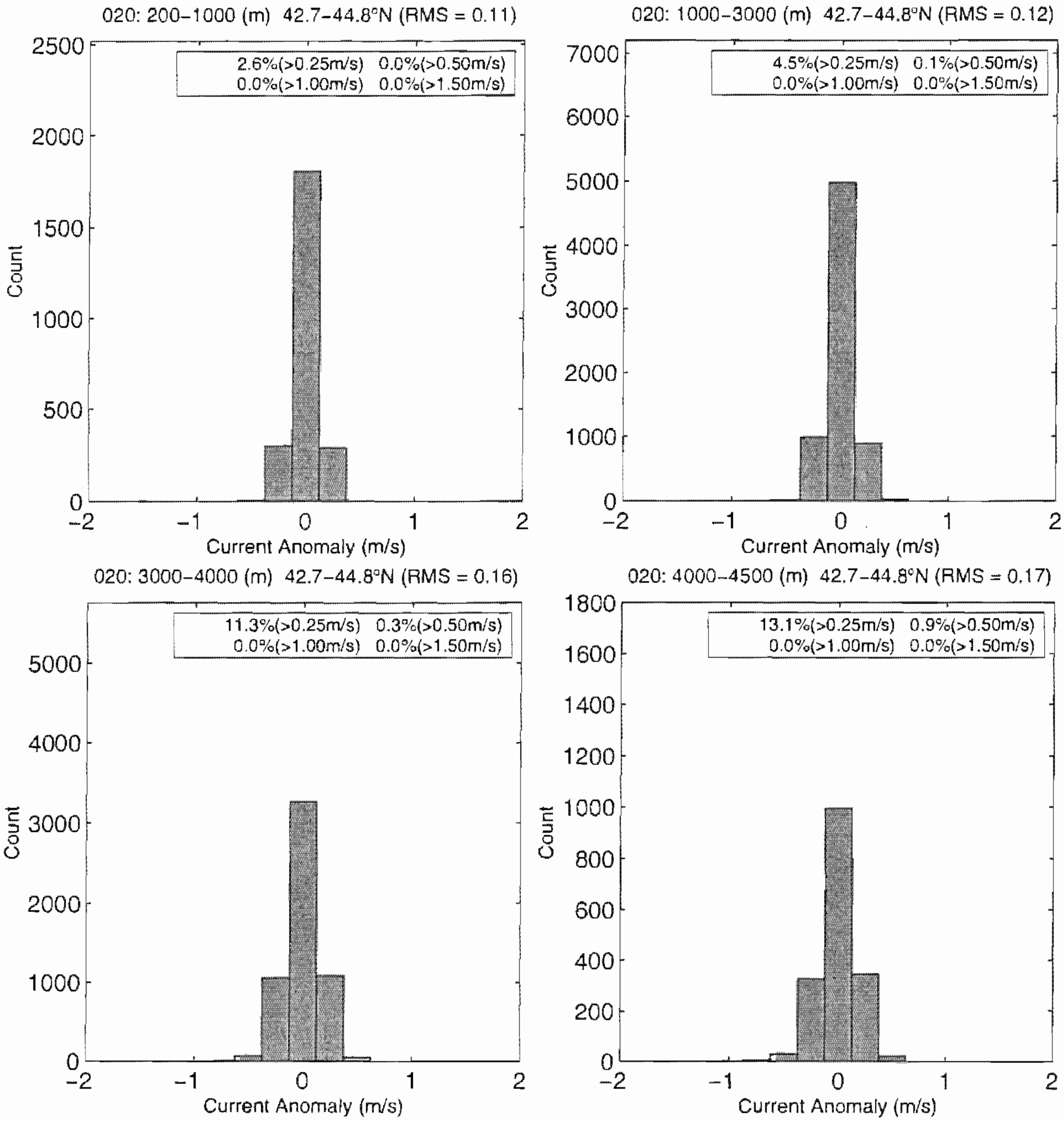
(a)

Figure 6. (a) Variability of the altimetric cross-track current anomalies from 1992 to 2002 plotted as twice the rms values. (b) Variability of the altimetric current anomalies at crossovers from 1992 to 2002 plotted as twice the rms values.



(b)

Figure 6. (continued).



(a)

Figure 7. Histograms of the altimetric current anomalies normal to the track over the southwestern Newfoundland Slope, for Tracks (a) 020, (b) 037, (c) 058, and (d) 096. The exceedance percentages for current anomaly magnitude are indicated in the inserts in each panel.

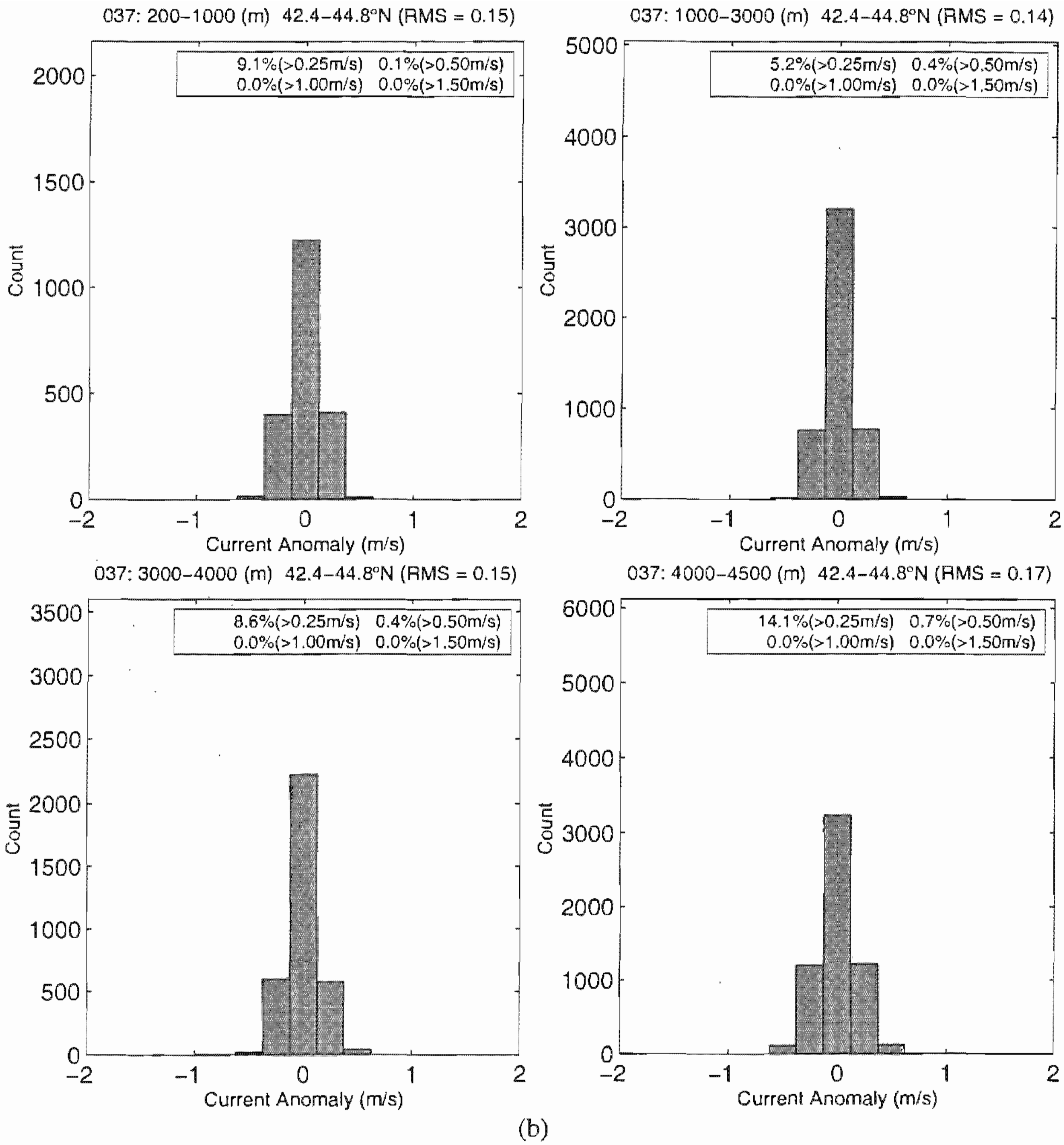
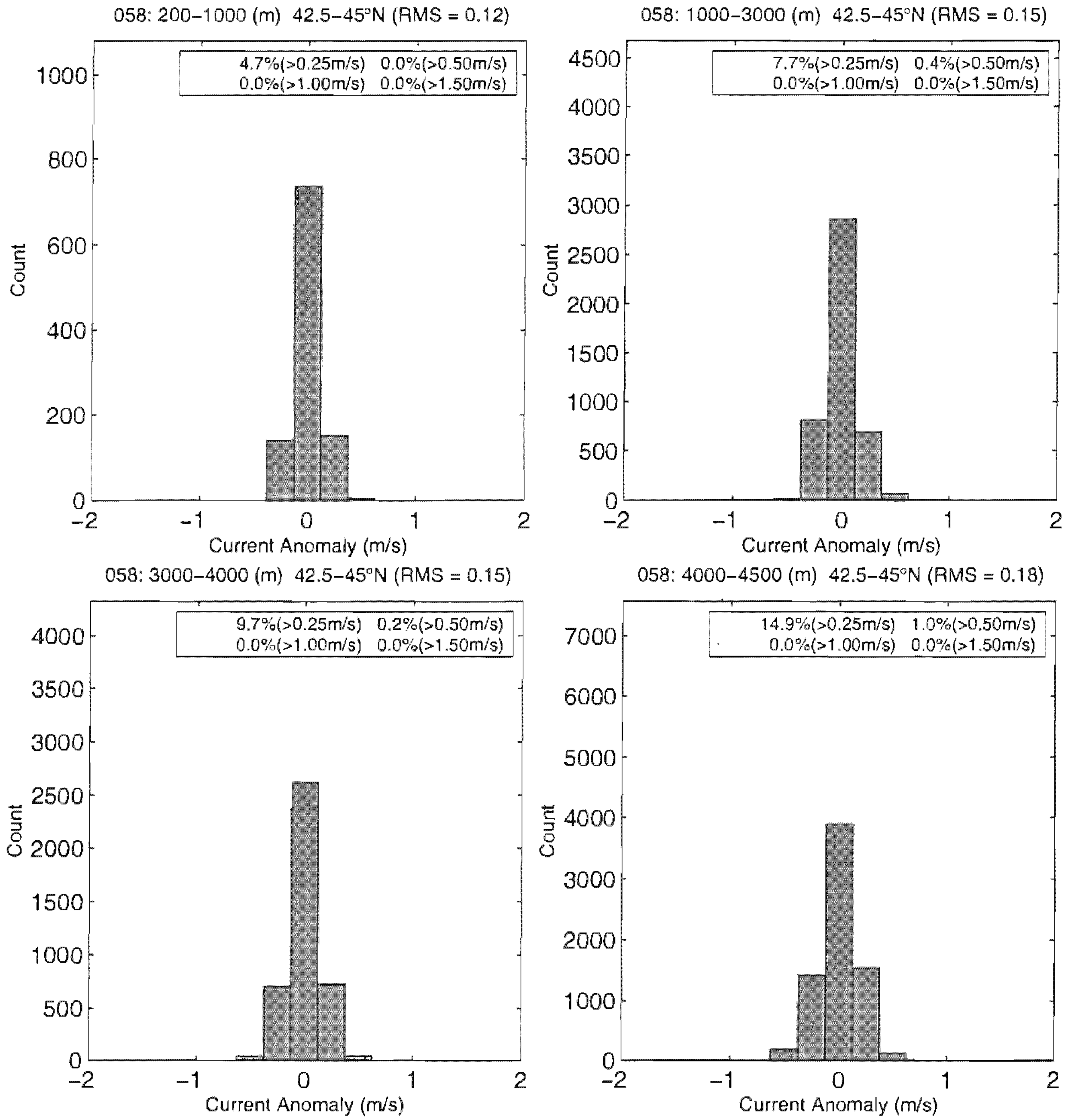
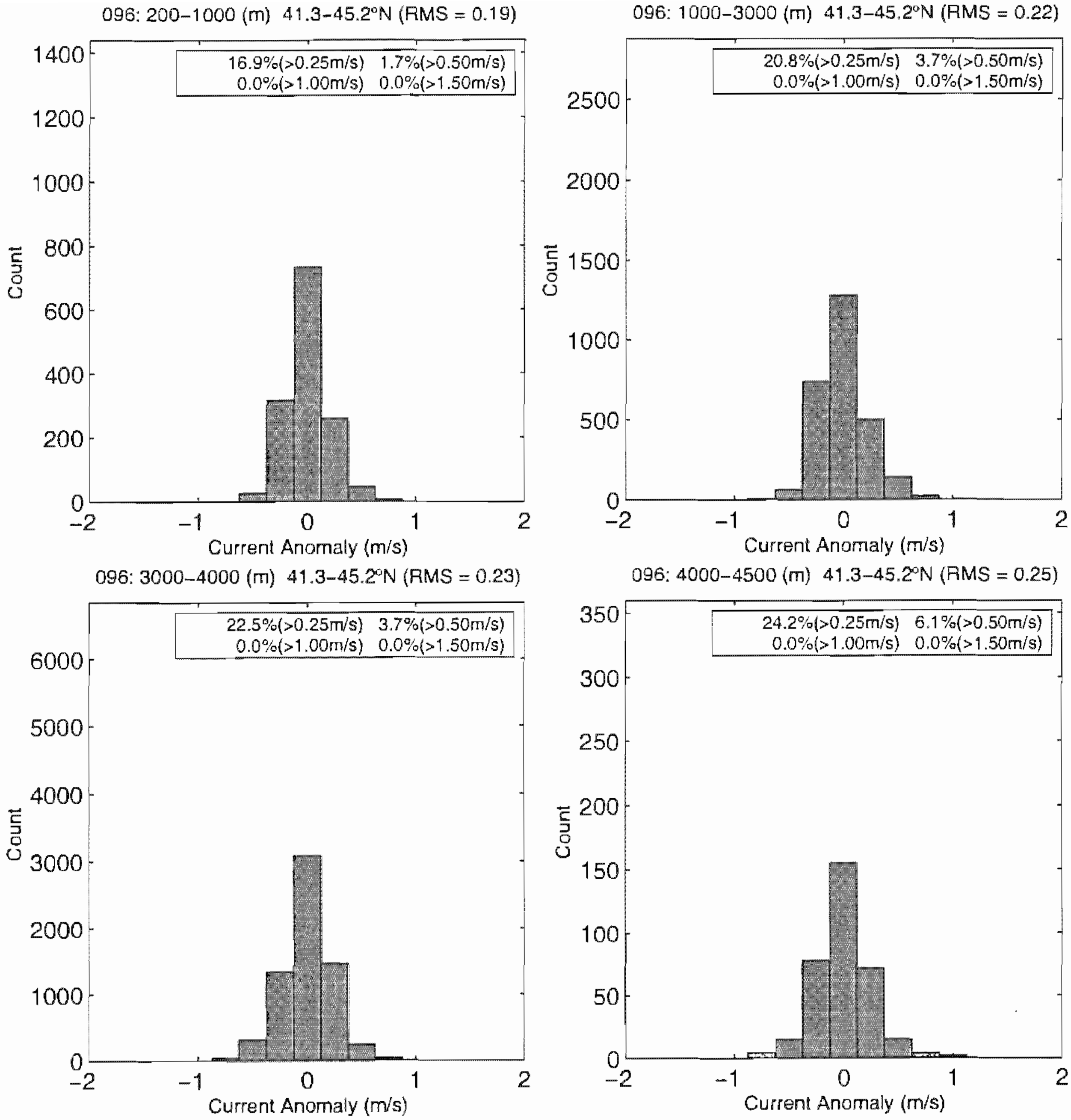


Figure 7. (continued).



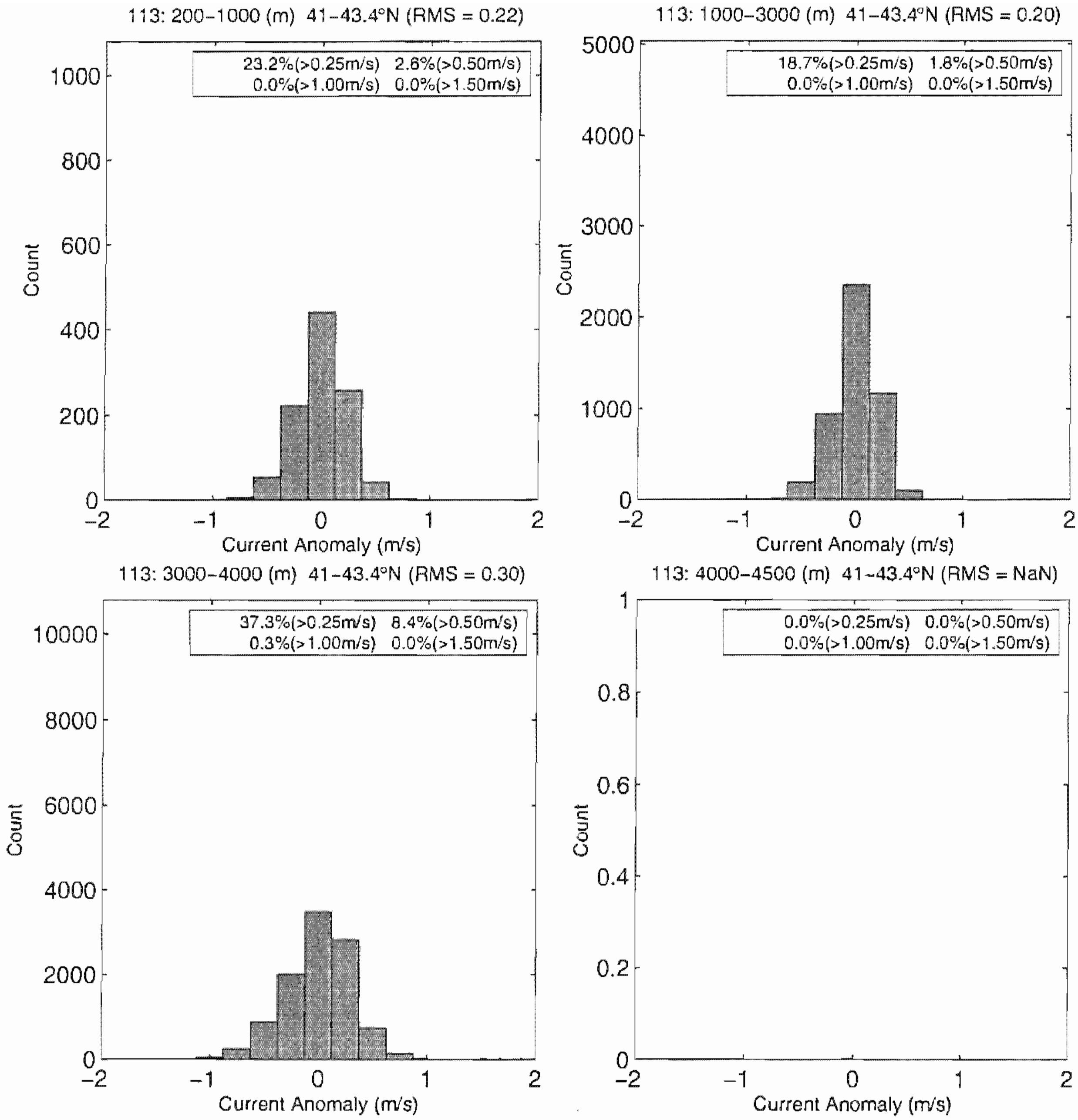
(c)

Figure 7. (continued).



(d)

Figure 7. (continued).



(a)

Figure 8. Histograms of the altimetric current anomalies normal to the track over the southeastern Newfoundland Slope, for Tracks (a) 113, (b) 024, (c) 062, and (d) 100. The exceedance percentages for current anomaly magnitude are indicated in the inserts in each panel.

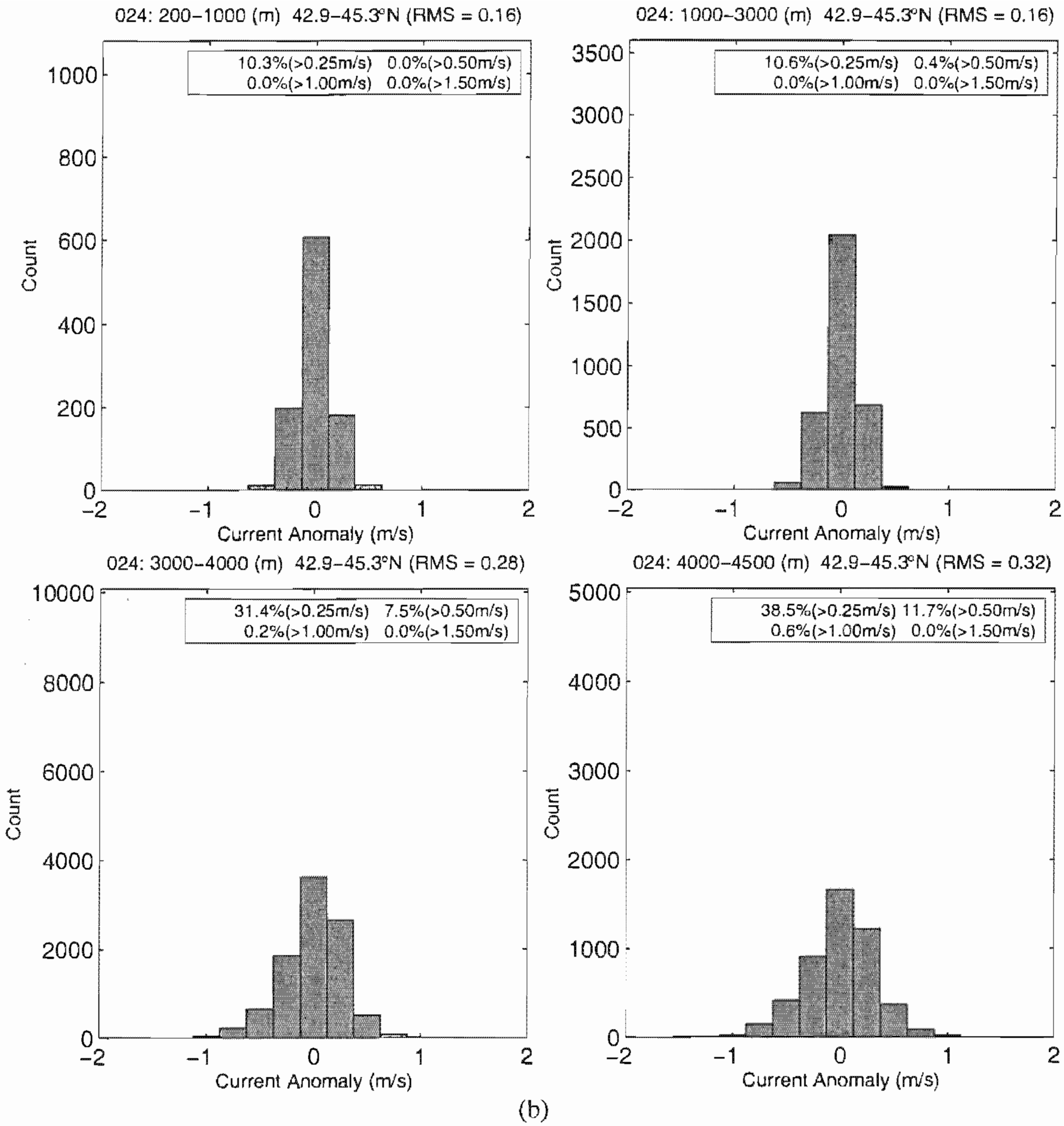


Figure 8. (continued).

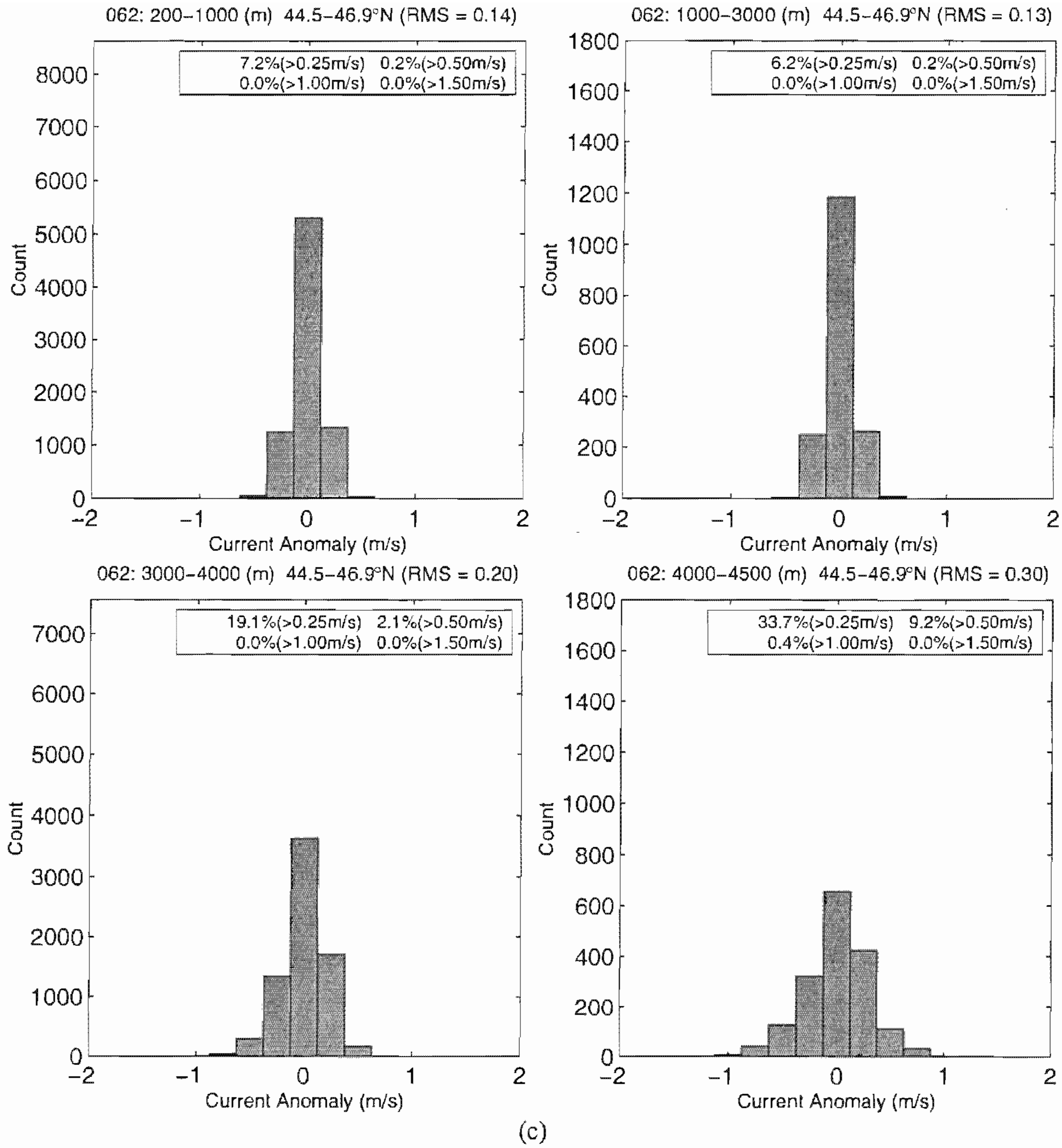
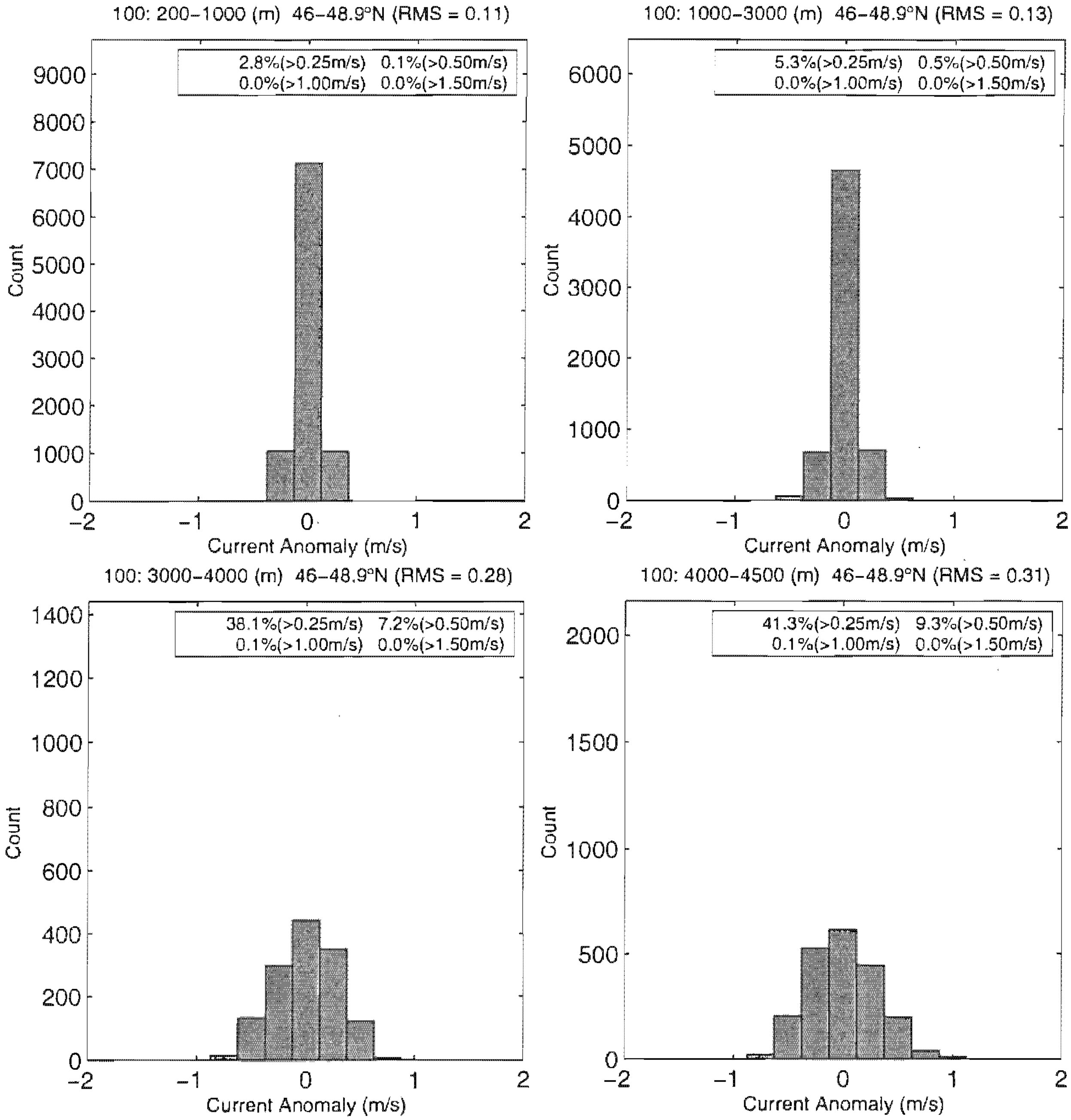
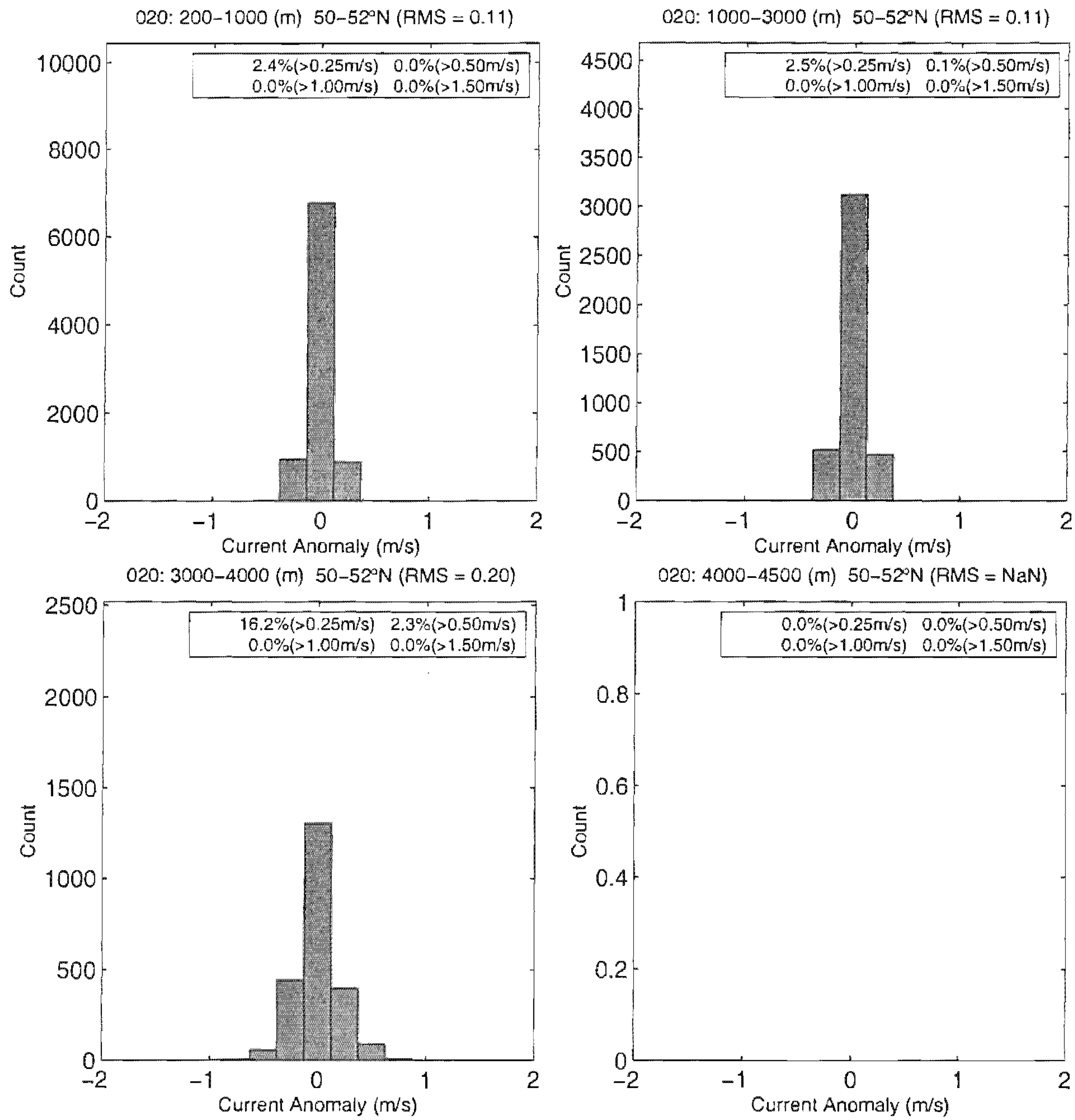


Figure 8. (continued).



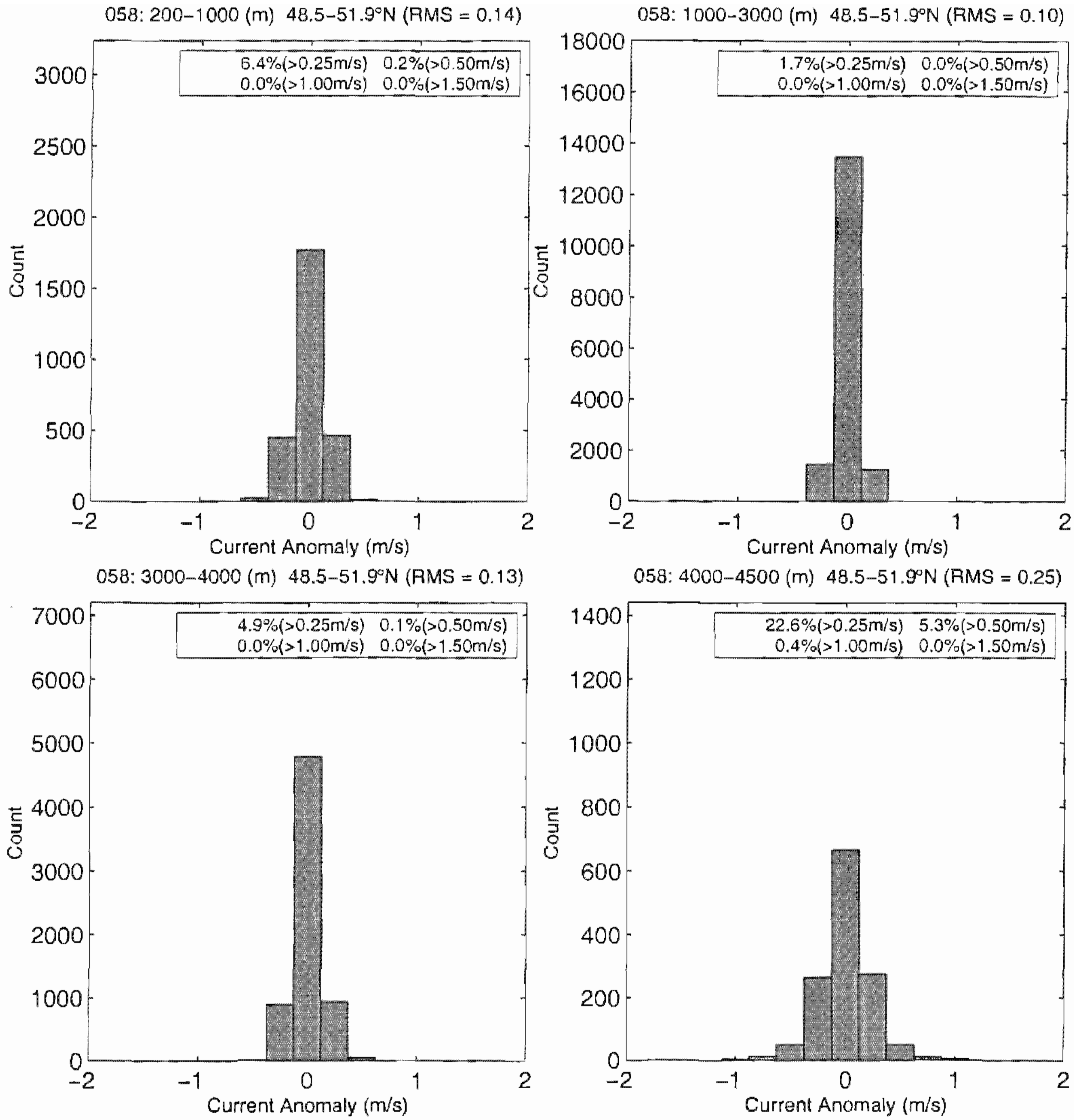
(d)

Figure 8. (continued).



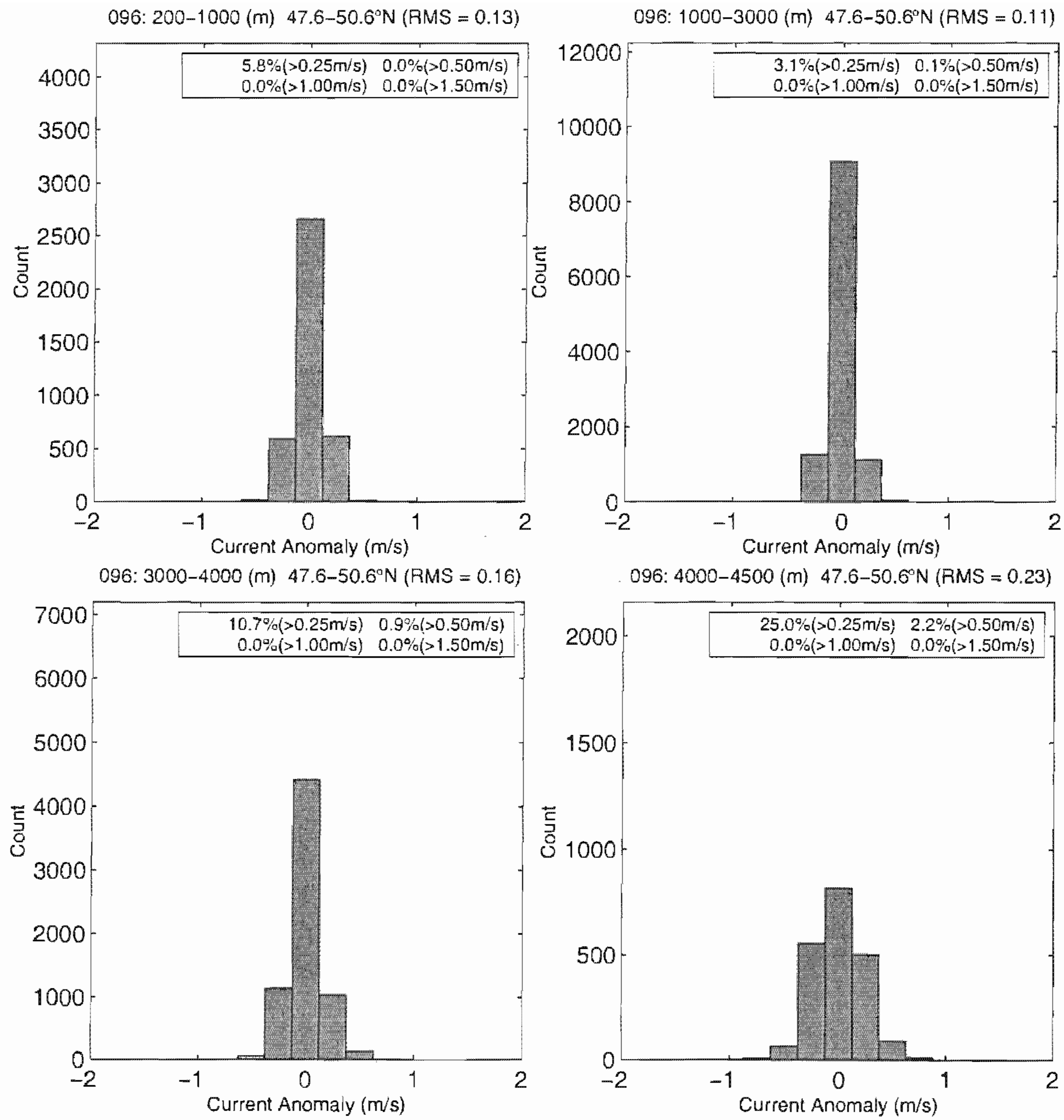
(a)

Figure 9. Histograms of the altimetric current anomalies normal to the track over the northeastern Newfoundland Slope, for Tracks (a) 020, (b) 058, (c) 096, and (d) 007. The exceedance percentages for current anomaly magnitude are indicated in the inserts in each panel.



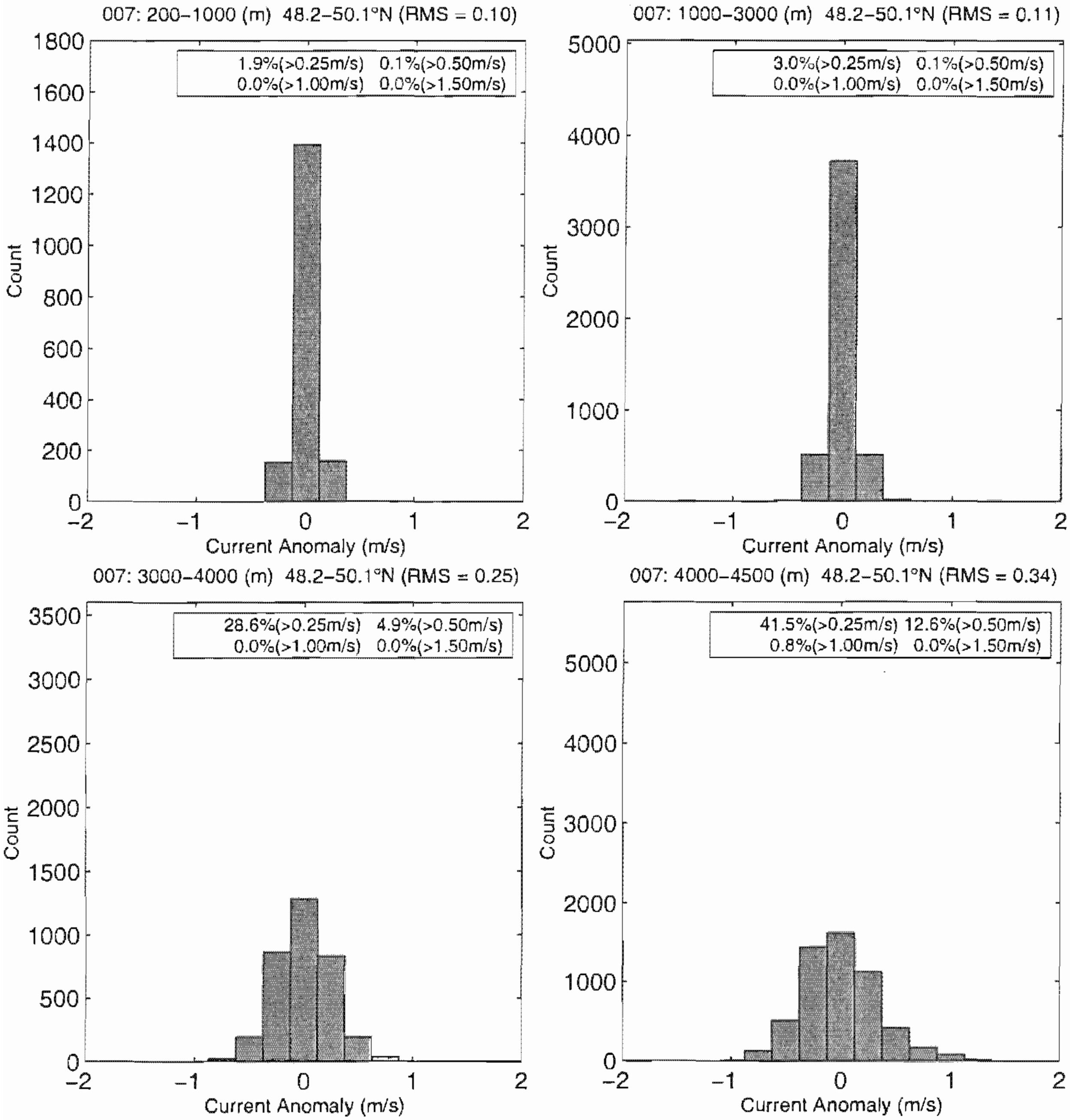
(b)

Figure 9. (continued).



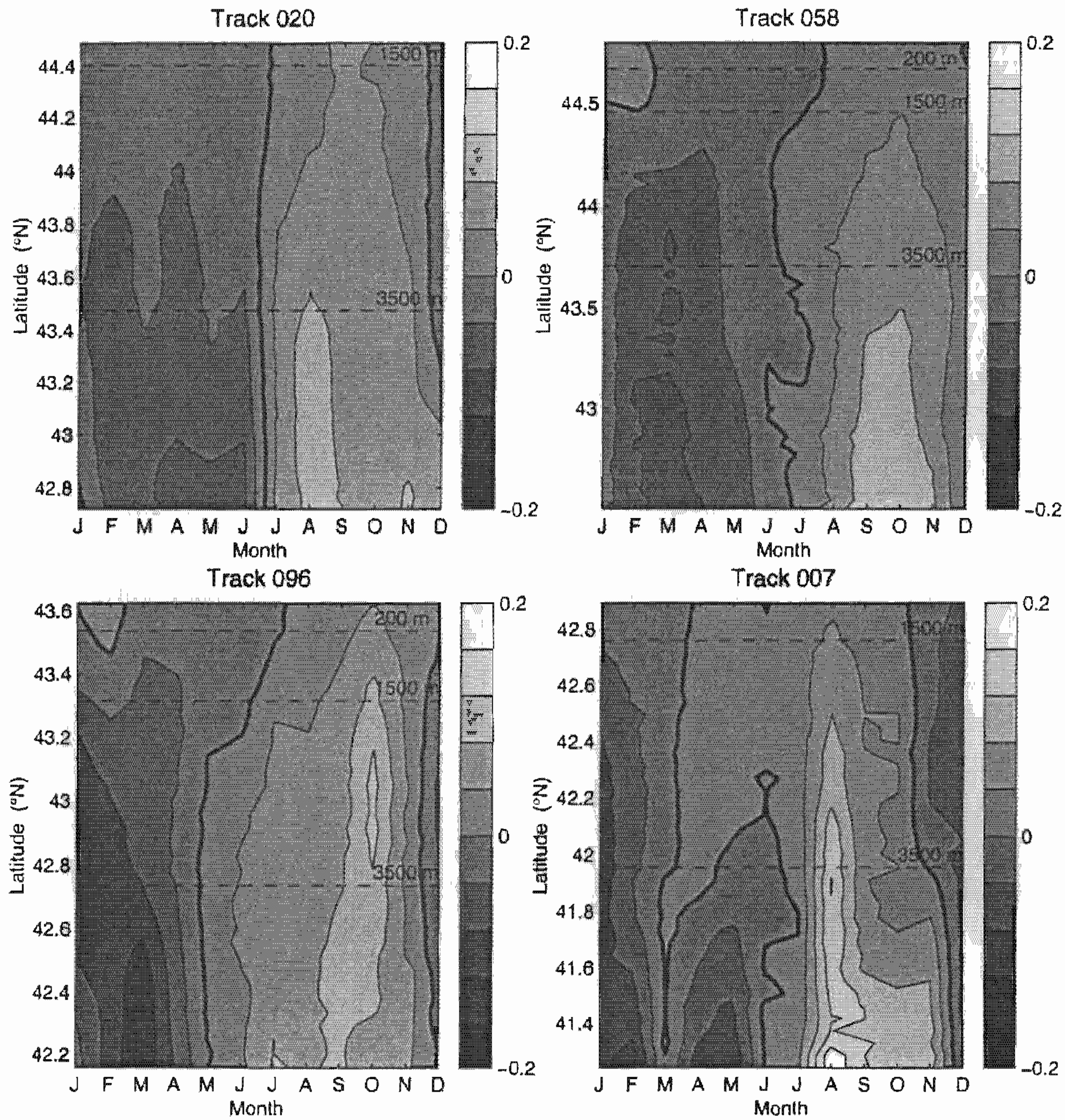
(c)

Figure 9. (continued).



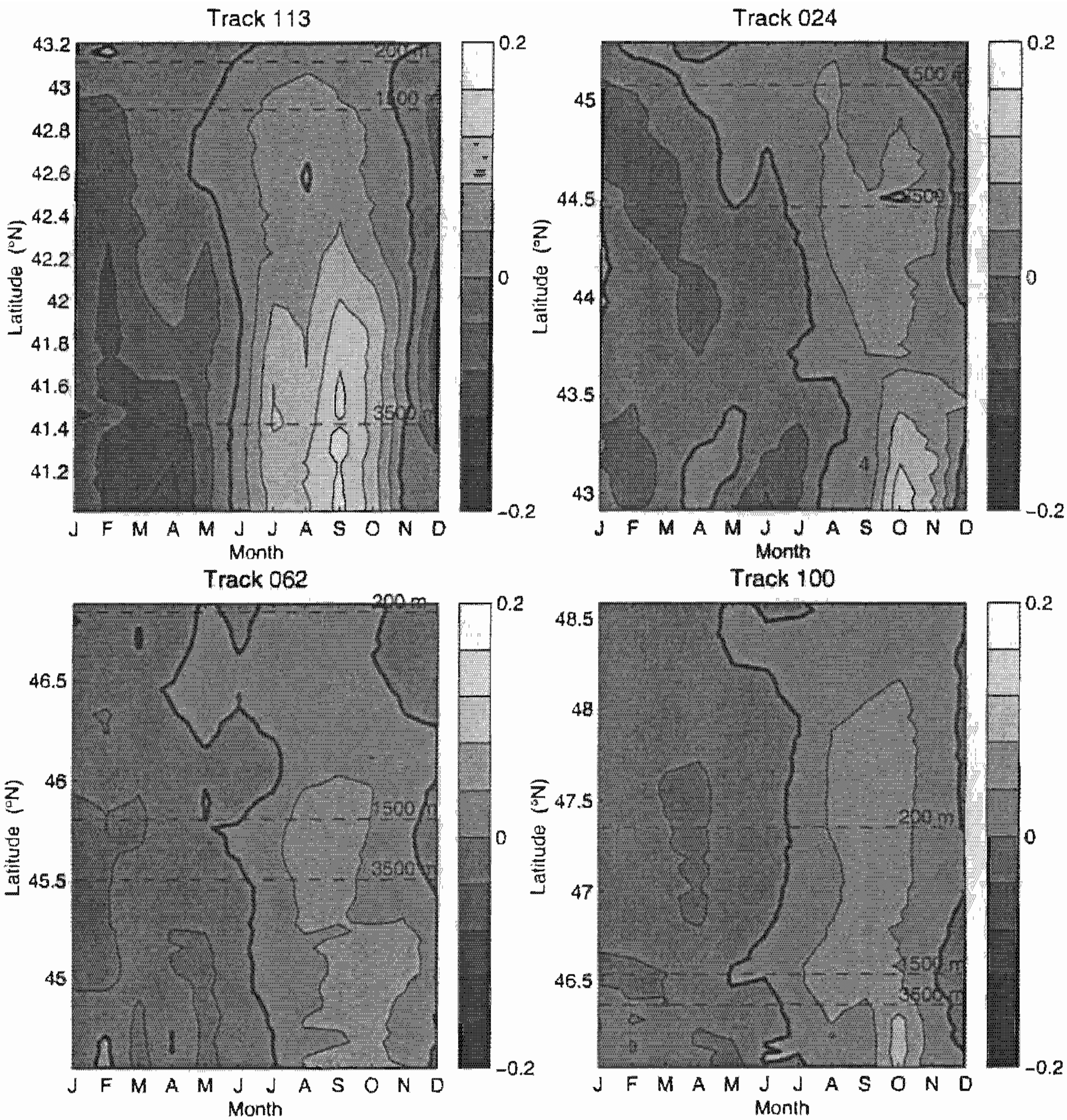
(d)

Figure 9. (continued).



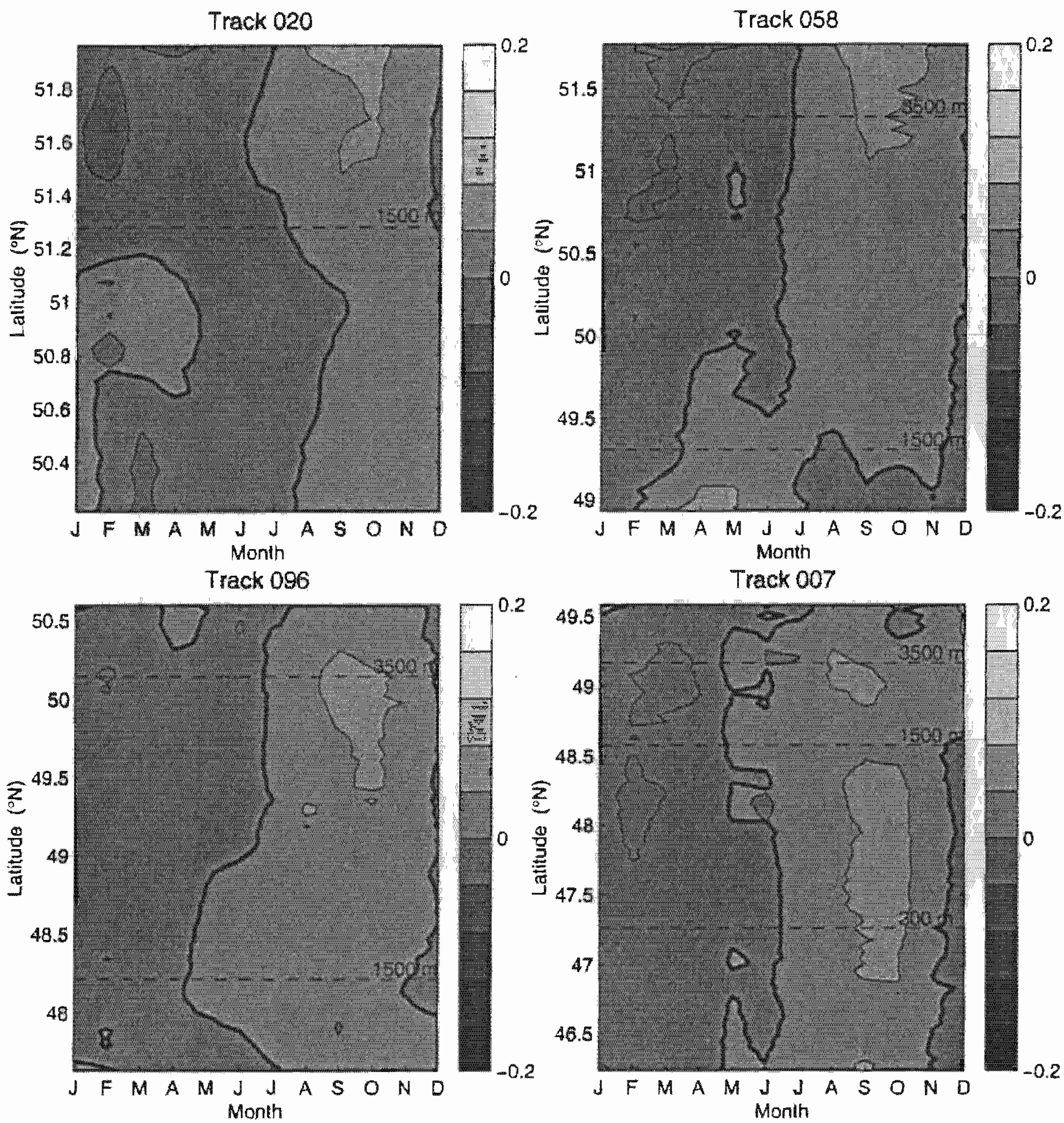
(a)

Figure 10. Along-track distribution of monthly sea level anomalies (m) from T/P data on the (a) SW, (b) SE and (c) NE Newfoundland Slope. The dashed lines indicate water depth. The zero contours are displayed in thick solid lines.



(b)

Figure 10. (continued).



(c)

Figure 10. (continued).

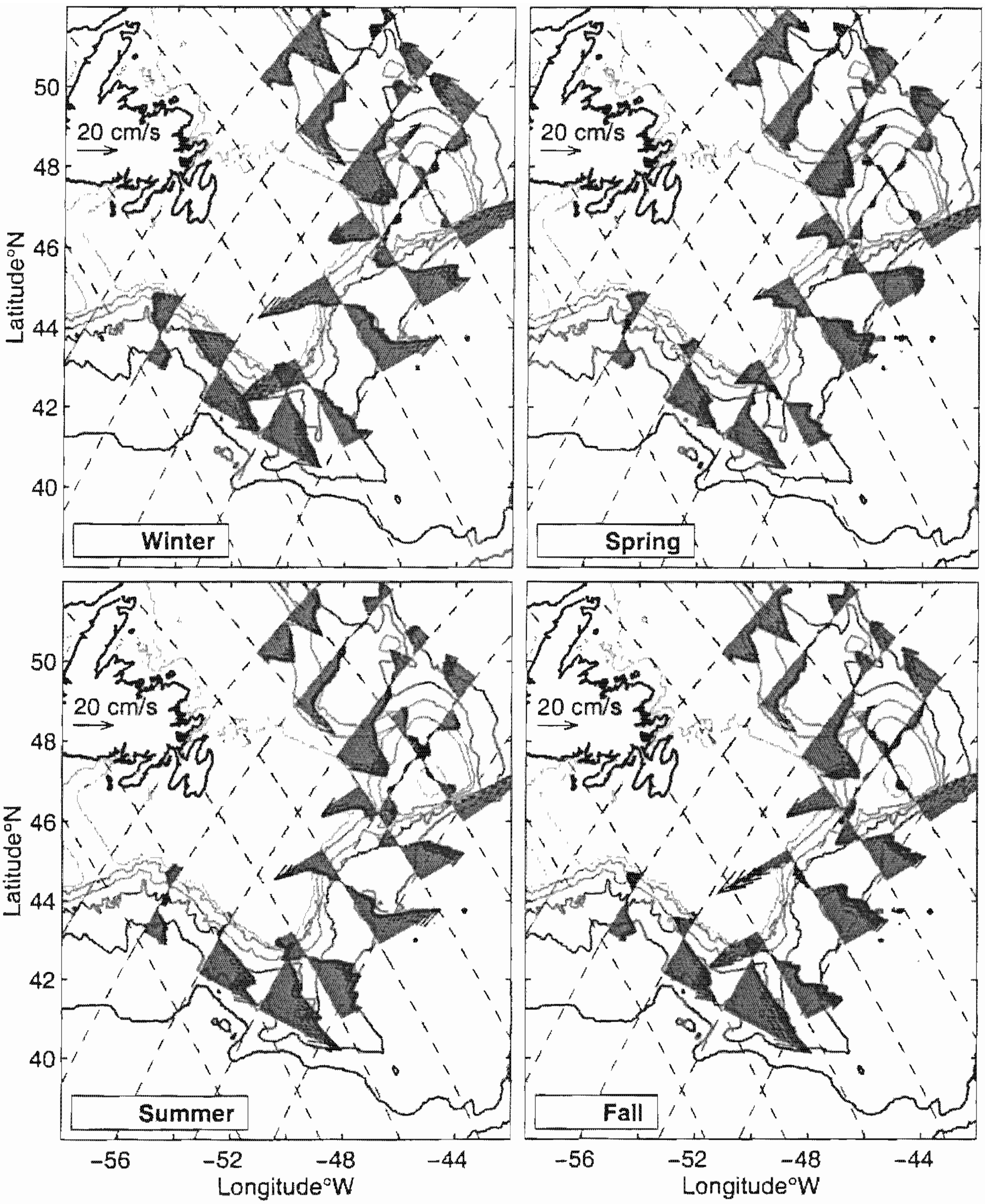
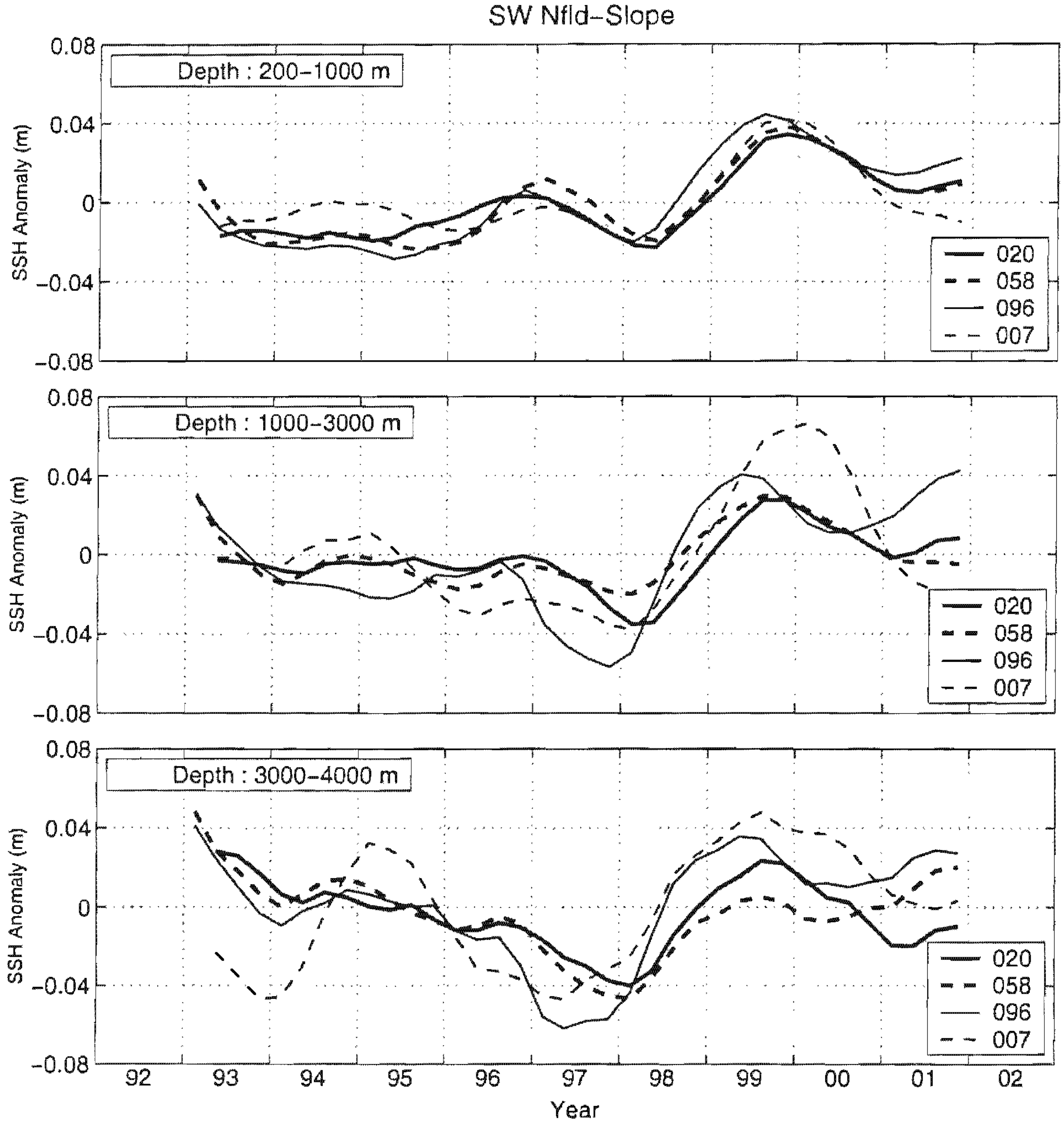
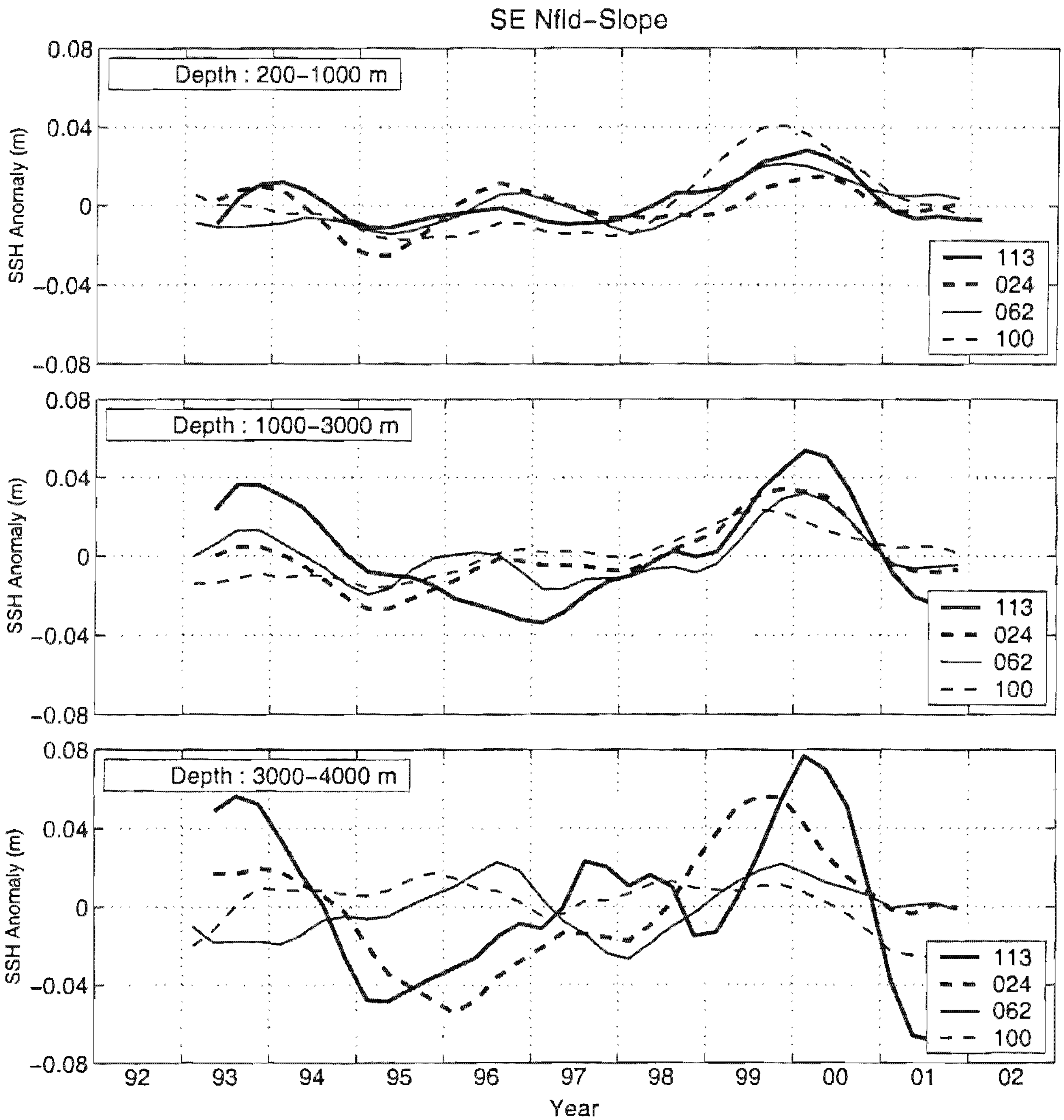


Figure 11. Seasonal-mean surface currents over the Newfoundland Slope in (a) winter, (b) spring, (c) summer and (d) fall: altimetric anomalies plus Han's (2003) model means.



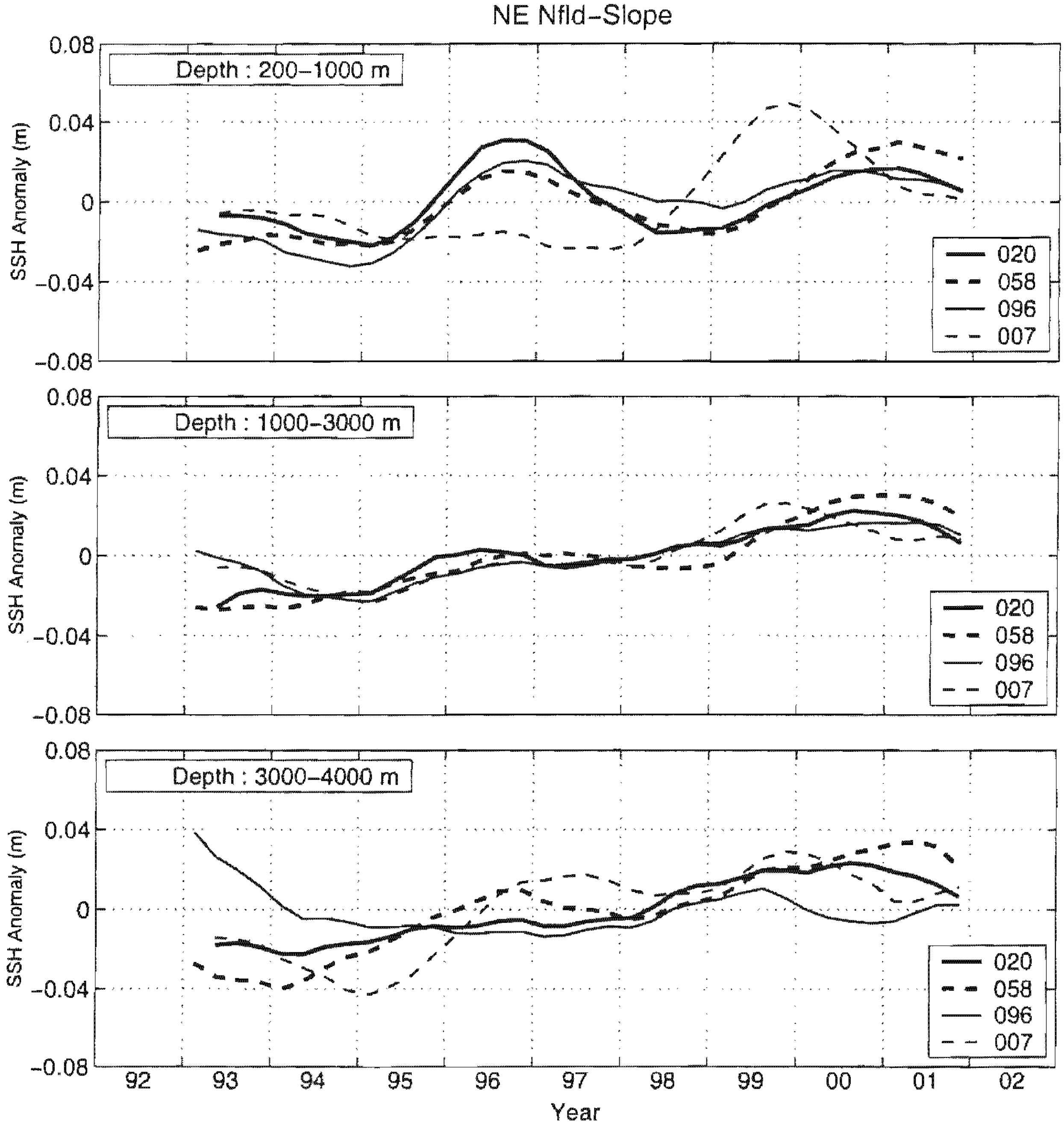
(a)

Figure 12. Seasonal-mean T/P sea level anomalies over the (a) SW, (b) SE and (c) NE Newfoundland Slope, averaged for three segments based on bathymetry. The seasonal means are smoothed with a five-point moving filter.



(b)

Figure 12. (continued).



(c)

Figure 12. (continued).

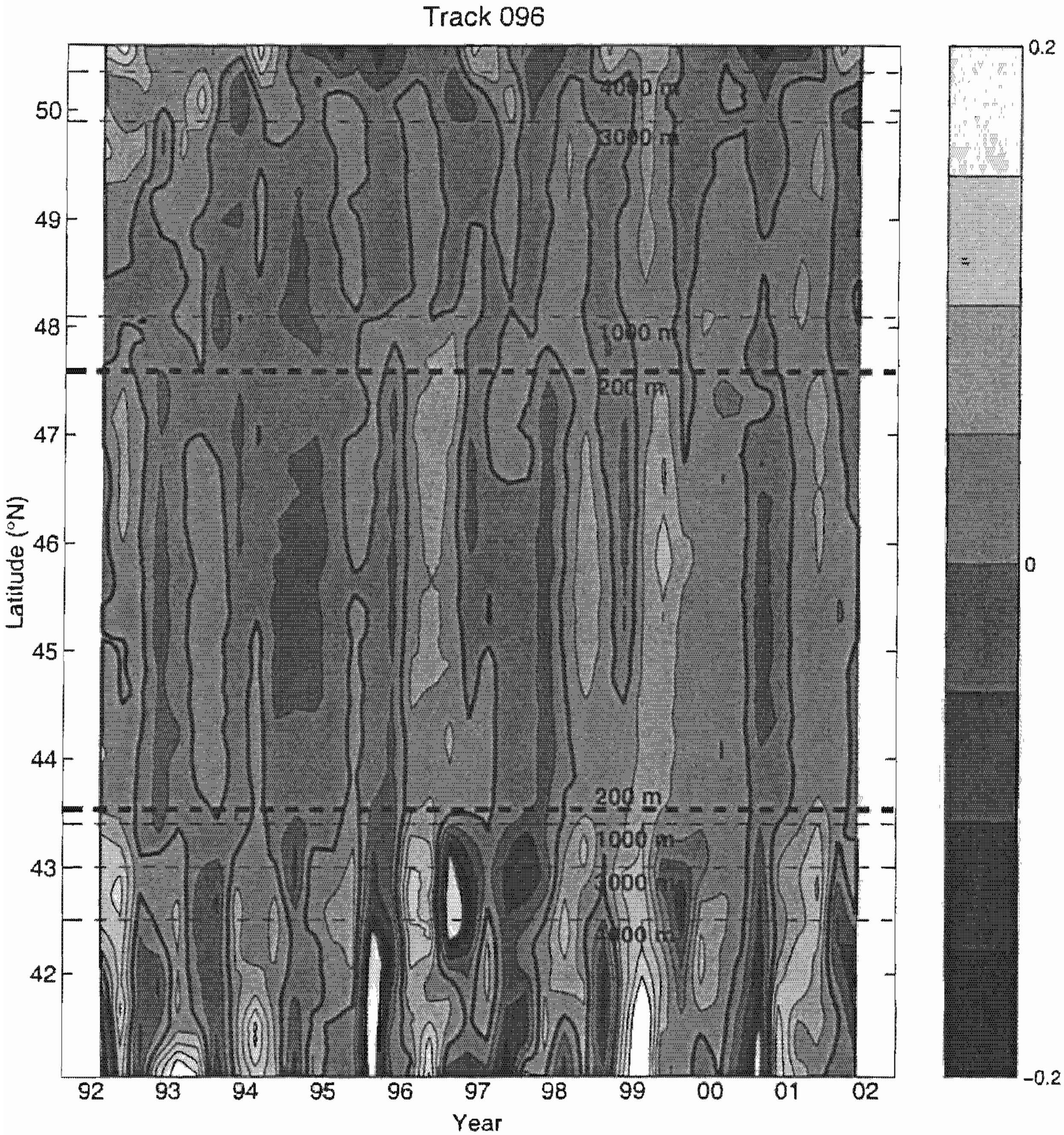


Figure 13. Seasonal-mean T/P sea level anomaly (m) distribution over the Newfoundland Slope in the time-latitude domain for track 096, including both the Grand Bank and Newfoundland Slopes. The seasonal mean anomalies are smoothed with a 5-point moving filter. The dashed lines indicate water depths. The zero contours are displayed in thick solid lines.

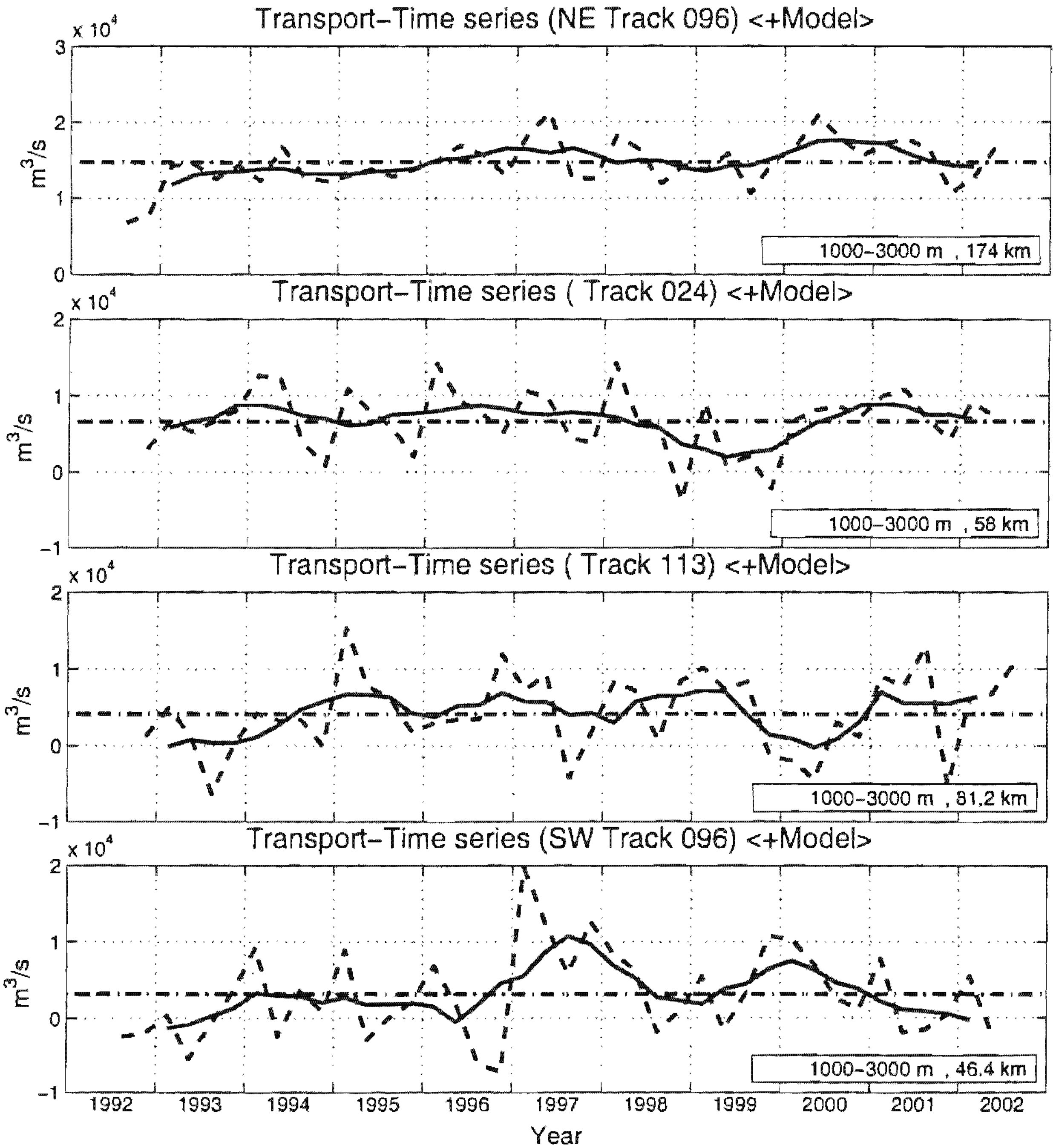


Figure 14. Surface (unit-depth) volume transport (positive equatorward between the 200-3000 m isobaths from altimetric seasonal-mean anomalies (dashed line) and Han's (2003) model means (dash-dotted line). The thick dashed line indicates the model component. The solid line shows interannual variability after the annual and semi-annual cycles are removed and a five-point moving filter is applied to the altimetric seasonal-mean anomalies.

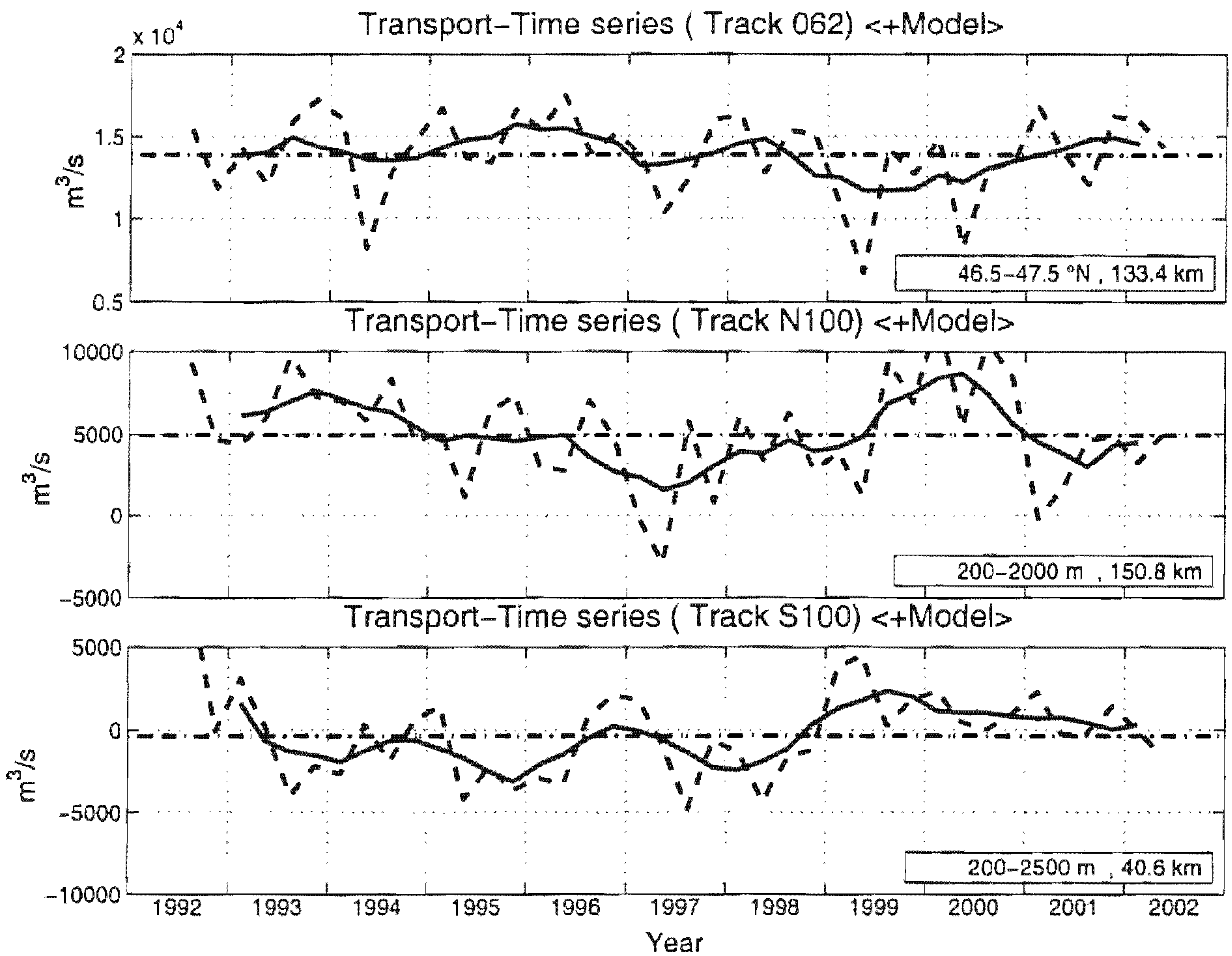


Figure 15. Surface (unit-depth) volume transport from altimetric seasonal-mean anomalies (dashed line) and Han's (2003) model means (dash-dotted line) for (a) Track 062 segment through the Flemish Pass (46.5-47.5N) (positive equatorward), (b) Track 100 segment on the northern flank of the Flemish Cap (200-2000m) (positive eastward), and (c) Tack 100 segment on the southern flank of the Flemish Cap (200-2500m) (positive westward). The solid line shows interannual variability after the annual and semi-annual cycles are removed and a five-point moving filter is applied to the altimetric seasonal-mean anomalies.