EVALUATION OF TANDEM TOPEX/POSEIDON-JASON DATA IN THE NEWFOUNDLAND OFFSHORE

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ABSTRACT

Han, G., and Li, J. 2005. Evaluation of tandem TOPEX/Poseidon-Jason data in the Newfoundland offshore. Can. Tech. Rep. Hydrogr. Ocean Sci. 244: vii + 21 p.

We have investigated sea level and surface currents features over the Newfoundland Shelf and Slope using the tandem TOPEX/Poseidon (T/P) and Jason altimetry data (2002-03). The consistency and error characteristics of T/P and Jason measurements are examined not only in terms of sea level and cross-track current anomalies but also with respect to current anomalies at crossovers and the Labrador Current transport. Nominal absolute currents are constructed by adding the altimetric geostrophic current anomalies to an annual-mean model circulation field. The comparison of the sea level and cross-track current anomalies from January to July 2002 shows overall good agreement between T/P and Jason, with correlation coefficients different from zero at the 5% significance level at almost all locations for sea level and at most locations for currents. Errors are estimated to be 2.5 cm for sea level and 10 cm/s for cross-track current anomalies. Analyses of the current variability at crossovers indicate approximate agreement of T/P and Jason measurements, except for the Northeastern Newfoundland Shelf and Slope probably due to the ice presence during the period. Model-altimetry combined absolute currents are used to estimate near-surface transport associated with the shelf-edge Labrador Current, showing good correlation between T/P and Jason estimates and strong seasonal changes. The cross-track geostrophic current anomalies from September 2002 to December 2003 are used to calculate the root-mean-square (rms) current variability at crossovers and to derive the shelf-edge Labrador Current. The interleaved T/P and Jason observations can better capture the spatial distribution of shelf and slope circulation variability.

RÉSUMÉ

Han, G., and Li, J. 2005. Evaluation of tandem TOPEX/Poseidon-Jason data in the Newfoundland offshore. Can. Tech. Rep. Hydrogr. Ocean Sci. 244: vii + 21 p.

Nous avons investigué les caractéristiques du niveau de la mer et des courants de surface sur la plate-forme et le talus de Terre-Neuve en nous servant des données TOPEX/Poséidon (T/P) et des données altimétriques Jason imbriquées pour 2002-2003. Nous avons examiné la cohérence et les caractéristiques de l'erreur des mesures T/P et Jason non seulement en termes des anomalies du niveau de la mer et des courants perpendiculaires à la plate-forme et au talus mais aussi en termes des anomalies des courants à leurs points d'intersection et du transport par le courant du Labrador. Nous avons ensuite reconstitué les courants absolus nominaux en ajoutant les anomalies altimétriques des courants géostrophiques à un modèle de champ de circulation fondé sur les moyennes annuelles. La comparaison des anomalies du niveau de la mer et des anomalies des courants perpendiculaires relevées entre janvier et juillet 2002 montre un bon niveau de concordance entre les données T/P et Jason, les coefficients de corrélation étant sensiblement différents du zéro, à un niveau de signification de 5 %, à presque tous les endroits pour le niveau de la mer et à la plupart des endroits pour les courants. Nos estimations de l'erreur la chiffre à 2,5 cm dans le cas du niveau de la mer et à 10 cm/s dans le cas des anomalies de courant perpendiculaire. Nos analyses de la variabilité des courants à leurs points d'intersection ont révélé que les données T/P et Jason concordent approximativement, sauf dans le cas du secteur nord-est de la plate-forme et du talus de Terre-Neuve, probablement à cause de la présence de glace à cet endroit pendant cette période. Nous avons regroupé les courants absolus établis d'après le modèle et les données altimétriques pour estimer le transport près de la surface associé au courant du Labrador en bordure de la plate-forme; une bonne corrélation entre, d'une part, les estimations T/P et Jason et, d'autre part, les changements saisonniers marqués, était évidente. Nous avons aussi utilisé les anomalies des courants géostrophiques perpendiculaires de septembre 2002 à décembre 2003 pour calculer les erreurs-types de la variabilité des courants aux points d'intersection et dériver le courant du Labrador en bordure de la plate-forme. Nous concluons que les observations T/P et Jason imbriquées capturent mieux la distribution spatiale de la variabilité de la circulation sur la plate-forme et le talus de Terre-Neuve.

INTRODUCTION

Near-surface ocean circulation in the Newfoundland offshore (Fig. 1) is dominated by the colder and fresher equatorward Labrador Current along the continental shelf edge and the warmer and saltier poleward Gulf Stream and the North Atlantic Current along the continental rise (e.g. Loder et al. 1998). Most of the shelf-edge Labrador Current continues along the northeastern Newfoundland Slope, through the Flemish Pass and toward the Tail of the Grand Bank. Some of the shelf-edge current extends further around the Tail of the Bank and along the southwestern Newfoundland Slope, while some turns offshore into the Newfoundland Basin (Petrie and Anderson 1983) to join the northeastward North Atlantic Current. An eastward branch of the shelf-edge Labrador Current north of Flemish Cap and south of Orphan Basin merges with the deep (lower slope) Labrador Current. Together they move around the Flemish Cap and then appear to be entrained into the North Atlantic Current east of the Cap.

Circulation variability over the Newfoundland Slope has traditionally been studied using drifters (e.g. Petrie and Anderson 1983; Pepin and Helbig 1997), moored measurements (e.g. Detracey et al. 1996) and numerical models (e.g. Hannah et al. 1985; Han 2003; Han and Wang 2005). In recent years satellite altimetry has been used to study sea level, currents and transport variability in this region (Han and Tang 1999, 2001; Fratantoni 2001; Han and Li 2004; Han 2004). Nevertheless, associated errors were not sufficiently quantified. In this study we use the tandem T/P and Jason altimeter data for the period from 2002 to 2003 to examine sea level and currents features over the Newfoundland Shelf and Slope. The tandem-mission data provide a unique opportunity of evaluating the consistency of T/P and Jason measurements and the error characteristics associated with altimetry–derived sea level and current anomalies. The shelf-edge current anomalies from altimetry are evaluated against moored measurements.

This article consists of five sections. The T/P and Jason data processing and surface-current derivation are described in Section 2. Section 3 examines the consistency between the T/P and Jason measurements from January to July 2002. Section 4 presents sea level and current results of the T/P and Jason observations from September 2002 to December 2003. Section 5 summarizes the report.

METHODOLOGY

T/P AND JASON ALTIMETER DATA

Altimetric sea-surface height data, which were corrected based primarily on the principles in Benada (1997) for various atmospheric and oceanographic effects and obtained from NASA Pathfinder Project, are the primary data sources in this study. The T/P and Jason data are used from January 2002 to July 2002, when both had the same ground tracks but with Jason leading slightly in time (hereinafter referred to as the near simultaneous tandem period) and from September 2002 to December 2003, when T/P had ground tracks shifted half-way between the Jason ground tracks (hereinafter referred to as the interleaved tandem period). The satellites repeat their ground tracks nominally every 10 days. Both T/P and Jason data have an along-track resolution of about 6 km. The standard NASA Goddard Space Flight Center precise orbit based on the Joint Gravity Model-3 has been used to produce the sea surface height data.

Ocean and load tides were corrected by a global ocean tide model (Ray 1999). The remaining tide variations over the Grand Banks, estimated to have an amplitude of 1 cm for M_2 and K_1 with apparent periods of 62 and 173 days respectively (Han et al. 2002), are considered negligible. Note that due to the sub-Niquest sampling of 10 days by T/P and Jason, semi-diurnal and diurnal tides are aliased into sea level variations at periods much longer than their physical ones.

For each tandem period, the corrected sea surface height data were used to generate a mean sea surface height field. We then calculated the sea surface height anomalies relative to the respective mean sea surface field. Both the marine geoid and mean oceanic topography are removed by this procedure. After a linear interpolation to fill the data gap, 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 on Track 096 for both T/P and Jason measurements are shown in Fig. 2 for March 3, 2002. The sea level anomaly is large (~1 m) in the vicinity of the Gulf Stream, substantial (~0.1 m) over the continental slope, and small over the Grand Bank.

CALCULATION OF GEOSTROPHIC SEA SURFACE CURRENT ANOMALIES

From the smoothed along-track altimetric sea surface height anomalies, we derived cross-track geostrophic surface current anomalies. The altimetric current anomalies for Track 096 on March 03, 2002 (Fig. 2) indicate significant current anomalies and spatial variability in the deep ocean. The current variability over the shelf edge and upper continental slope is also prominent. Note that these are estimates of surface current anomalies normal to the satellite ground tracks about the mean only (See Fig. 1 for schematic pattern of the mean flow across Track 096), associated with the along-track pressure gradient derived from the slope of sea surface.

T/P AND JASON NEAR SIMULTANEOUS TANDEM MEASUREMENTS

For the period from January 2002 to July 2002, the T/P and Jason missions have the same nominal ground tracks with the latter leading slightly in time. The near simultaneous measurement provides an opportunity of evaluating the consistency of the T/P and Jason data in observing sea level and currents over the Newfoundland Shelf and Slope.

SEA LEVEL AND CROSS-TRACK CURRENT ANOMALIES

We calculated rms variability (Fig. 3a and 3b) of the T/P and Jason sea level time series and correlation between the two time series (Fig. 3d) for selected tracks. As we can see, both T/P and Jason indicate increased sea level variability offshore and westward. The values vary from 5-10 cm over the continental slope to 20 cm in the lower slope. The correlation coefficients between the T/P and Jason data are generally high (Fig. 3d), 97.2% of which are significantly different from zero at the 5% significance level. The average correlation coefficients are 0.94 over the Grand Banks (depth <200 m) and 0.90 in the deeper ocean (depth >200 m). The rms difference is significantly smaller (especially near the Gulf Stream and its extension the North Atlantic Current) than either the T/P or Jason variability over most areas (Fig. 3c). The average rms difference is 3.1 cm over the Grand Banks (shallower than 200 m) and 3.5 over the continental slope and rise (from the 200- to 4500-m isobath).

The noise in the altimetric data can be estimated by comparing T/P and Jason measurements interpolated to a common time by assuming geophysical sea level changes are measured coherently and the noise is incoherent. If the noise in the T/P and Jason time series is assumed to be uncorrelated and to be of equal variance the noise can be estimated as half the variance of the difference time series. Therefore, the average sea level error is about 2.5 cm. Based on this assumption we have derived the T/P and Jason signal-to-noise variance ratios, shown as twice of their square root values in Fig. 3e and 3f. The signal-to-noise variance ratio is generally high both over the shelf (25) and in deeper oceans (35), which is in contrast with the sharp spatial contrast off Nova Scotia, where the ratio is very high (>100) in the deep ocean and high (10) over the shelf and lower continental slope, and moderate (5) over some areas of the upper continental slope (Han 2004).

A similar analysis is carried out for the geostrophic surface current anomalies. The variability increases offshore in both T/P and Jason data (Fig. 4a and 4b). The values vary from 15 cm/s over the shelf to 30-50 cm/s over the slope and deeper ocean. Overall the T/P and Jason correlation for currents is lower compared to that for sea level (Fig. 4d and 3d), but remains significantly different from zero at the 5% significance level at most locations (83.5%). The correlation was generally lower over the northeastern Newfoundland Shelf and Slope, due to data loss or data quality degradation as a result of ice presence during the winter months. The average correlation coefficient over the shelf is 0.5 and the value is 0.7 over the slope and in the deep ocean. The rms differences are 13.1 and 15.6 cm/s over the shelf and over the slope, respectively. The corresponding rms error estimates are 9 and 11 cm/s for the shelf and for the deeper ocean. The signal-to-noise variance ratio is about 2-4 over the shelf and 10 over the slope and in the deep ocean (Fig. 4e and 4f). The offshore increase in the signal-to-noise ratio is primarily due to the increased current variability associated with the proximity to the Gulf Stream or the North Atlantic Current (meanders and frontal eddies).

CURRENTS AT CROSSOVERS

The rms variability of the total current can be estimated from altimeter data at crossovers of descending and ascending tracks (Han 2004). We have interpolated cross-track geostrophic current anomalies along-track onto crossover locations (see Fig. 1 for locations) at a common coordinate. The cross-track components are then transformed into the eastward and northward components, from which the total rms current variability is calculated. Total rms variability ranges from 20 to 50 cm/s over the southwestern and southeastern Newfoundland Slope, while that is at 10-20 cm/s over the Grand Banks (Tables 1 and 2). There are large differences between T/P and Jason results over the northeastern Newfoundland Shelf and Slope due to more missing data as a result of ice presence during the period. The mean difference (T/P minus Jason) and its standard deviation for the total rms magnitude are -2.6 ± 4.5 cm/s with an rms difference of 5.1 cm/s including all crossovers and -1.6 ± 4.7 cm/s with an rms difference of 4.8 cm/s excluding those over the northeastern Newfoundland Shelf and Slope.

We have calculated the ratios of the rms current values on the descending or ascending tracks to the total rms current variability (d/t and a/t for descending and ascending tracks, respectively). Although the d/t or a/t values can differ significantly among the crossovers, the averages of the d/t and a/t values are less variable. The average ratio of d/t and a/t varies from 0.60 to 0.79 with a mean of 0.68 for T/P and from 0.61 to 0.76 with a mean of 0.68 for Jason. The mean difference (T/P minus Jason) and its standard deviation between the T/P and Jason estimates are 0.00 ± 0.04 for the average of d/t and a/t values. It appears that the total current variability can be estimated by a factor of 1.5 from the average of the cross-track rms values of the descending and ascending tracks. The ratio statistics are not sensitive to the exclusion of the crossovers over the northeastern Newfoundland Shelf and Slope.

Major and minor axes of the current ellipsis, orientation of the major axis, and ratio of the minor to major axes can be derived from the eastward and northward current components. There seems to be good agreement between T/P and Jason results, except over the northeastern Newfoundland Shelf and Slope. The major axis varies from 10 over the Grand Banks to 50 cm/s offshore in the proximity of the Gulf Stream or the North Atlantic Current. Excluding the crossovers over the northeastern Newfoundland Shelf and Slope, the rms differences between the T/P and Jason are 6.0 cm/s, 7 degrees (also excluding F) and 0.15 for the major axis, angle, and ellipse ratio, respectively. The ratio of minor to major axes at the crossovers vary from 0.18 to 0.88 with a mean of 0.50 for T/P (Table 1) and from 0.22 to 0.75 with a mean of 0.50 for Jason (Table 2). The mean difference (T/P minus Jason) and its standard deviation between the T/P and Jason estimates are 0.00 ± 0.18.

THE SHELF-EDGE LABRADOR CURRENT

We have calculated volume transport anomalies for 096 on the NE slope, 024 and 113 on the SE slope and for 096 on the SW slope from the 200- to 3000-m isobaths and from the surface to the 200-m depth using the altimetric geostrophic current anomalies (Fig. 5a, b, c and d). Climatological annual-mean surface currents from Han's (2003) finite-element model solutions are interpolated onto the satellite ground tracks and the components normal to the track are then derived for the calculation of the mean transport. The sum of the model annual mean and the altimetric anomalies is used as a proxy to the total transport. The total transport values can nominally represent the strength of the shelf-edge current, in spite of limitations such as the assumption of depth-invariable current and the use of partial water column only. Note that the use of the surface current compensates for that of the partial water column.

The results from the T/P and Jason data are in approximate agreement. The rms transport magnitude is 6.1 (6.2), 2.5 (3.0), 2.4 (2.8), and 2.0 (1.9) Sv (1 Sv = 10^6 m^3/s) for T/P (Jason) on Tracks NE096, 088, 050 and SW096. The correlation coefficient between T/P and Jason is 0.28, 0.65, 0.93 and 0.84, all different from zero at the 5% significance level except for the first track (also see Fig. 4) and the rms difference is 1.31, 0.94, 0.82, and 0.95 Sv for the four tracks. The seasonal-mean transport values for the winter (January–March) and spring (April–June) seasons of 2002 are given in Table 3. The T/P and Jason agree well in the seasonal changes, which show a stronger flow in winter than in spring, except for Track NE096. The transport is generally equatorward and decreases downstream, probably associated with the retroflection of the Labrador Current (Loder et al. 1998).

We have also averaged the transport values for the four T/P and Jason tracks, respectively (Fig. 5e). The rms transport value is 2.9 and 3.0 Sv for T/P and Jason respectively. The correlation coefficient is high at 0.89 (different from zero at the 5% significance level) and the rms difference is low at 0.5 Sv. The T/P-based transport is 3.1 and 2.5 Sv in winter and spring, comparable to the Jason-based transport of 3.3 and 2.6 Sv in the respective seasons.

T/P-JASON INTERLEAVED TANDEM MEASUREMENTS

For the period from September 2002 to December 2003, the T/P and Jason missions have interleaved ground tracks. Therefore the cross-track resolution is doubled (at about 110 km for this region) and the crossovers are quadrupled (Fig. 6). In this section we examine first the current variability at crossovers and then the shelf-edge Labrador Current transport from the interleaved T/P and Jason observations.

CURRENTS AT CROSSOVERS

Geostrophic surface current anomalies are examined in three groups: T/P-T/P, Jason-Jason, and T/P-Jason crossovers (Fig. 6). The results are combined to examine spatial variability and to derive overall statistics. Similar to Section 3.2, we have interpolated cross-track geostrophic current anomalies onto crossovers at a common time coordinate. An advantage during the interleaved tandem mission is a quadruple increase of crossovers and therefore a better representation of the current spatial variability.

For T/P crossovers the total rms variability is 10-40 cm/s smaller over the shelf and larger offshore (Fig. 6). The average ratio of d/t and a/t varies from 0.67 to 0.73 with a mean of 0.69 (Table 4). For Jason crossovers the total rms variability is 10-60 cm/s, generally supporting the spatial pattern from T/P. The average ratio of d/t and a/t varies from 0.63 to 0.74 with a mean of 0.69. Therefore, there is little difference among the mean ratios for the T/P and Jason crossovers. The mean ratio for all the T/P, Jason, and T/P-Jason crossovers is estimated to be 0.70 with a standard deviation of 0.03, which is also close to those obtained for the Scotian Slope (Han 2004).

However, both T/P and Jason observations indicate significant spatial variations. The discrepancies between the T/P and Jason rms current values are a representation of high spatial differences of current variability in the region and insufficient spatial resolution by either T/P or Jason mission. Evidently, neither T/P nor Jason can well capture the spatial characteristics of current variability, especially along the Newfoundland Slope. With the interleaved T/P and Jason data, observations of the spatial features are significantly improved. We can see the current variability is weakest ove the central Grand Bank and in the Orphan Basin (10 cm/s), and largest near the Gulf Stream and the North Atlantic Current (60 cm/s), and in between over the upper and lower continental slope (15-40 cm/s).

From the eastward and northward current components, major and minor axes, orientation of the major axis, and ratio of the minor to major axes can be derived. The ratios at the crossovers vary from 0.44 to 0.76 with a mean of 0.55 for T/P and from 0.33 to 0.86 with a mean of 0.57 for Jason. In terms of their standard deviations (0.1-0.2), the average ratios are not different statistically. The mean ratio for all the T/P, Jason and T/P-Jason crossovers is estimated to be 0.59 with a standard deviation of 0.15. Compared with that over the Scotian Slope (Han, 2004), the current variability over the Newfoundland Shelf and Slope seems to be less anisotropic on a whole, but the statistical significance of the difference remains to be a question.

THE SHELF-EDGE LABRADOR CURRENT

Volume transport from the 200- to 3000-m isobath for the T/P and Jason tracks is calculated using the method described in Section 3.3 (Fig. 7a-d). The interleaved scheme increases the resolution in the along-slope direction and therefore can better reveal the along-stream transport variation of the Labrador Current. The rms transport magnitude is 6.2 (6.3), 2.9 (2.8), 3.6 (2.1), and 1.5 (1.8) Sv for T/P (Jason) on Tracks NE096, 024, 113 and SW096. The transport averaged for the T/P tracks is generally compatible with that for the Jason tracks, but with a low correlation coefficient of 0.2 and an rms difference of 1.6 Sv. The rms transport magnitude is 2.7 and 2.9 Sv from T/P and Jason, respectively. It is not surprising to see the much lower correlation and the relatively larger rms difference during the interleaved tandem period than during the near simultaneous tandem period, because the T/P and Jason tracks in the former are apart from each other by approximately 100 km in the along-isobath direction.

The T/P and Jason results also show a consistent seasonal cycle. From the combined T/P and Jason results (Fig. 7e), the seasonal mean transport associated with the shelf-edge current is strongest in winter (3.6 Sv) and weakest in fall (1.8 Sv).

SUMMARY

We have used T/P and Jason tandem altimeter data from 2002 to 2003 to evaluate their consistency and synergy for studying sea level and current variability over the Newfoundland Shelf and Slope. The evaluation is conducted for sea level anomalies, cross-track geostrophic current anomalies, current anomalies at crossovers, and the Labrador Current transport.

A comparison of the T/P and Jason data for the near simultaneous tandem period in the first half of 2002 indicates overall consistency with statistically significant correlation in sea level for essentially all locations and in cross-track surface geostrophic current anomalies for the majority of the locations. The rms errors are estimated to be 2.5 cm for sea level and 10 cm/s for cross-track current anomalies. Analyses of vector current anomalies at crossovers also indicate approximate agreement between T/P and Jason estimates. The near-surface transport associated with the Labrador Current estimated from the two datasets agrees well.

The results during the interleaved tandem period reveal compatible properties from T/P and Jason measurements. Crossover analysis indicates a significant improvement of the interleaved T/P-Jason observation scheme in resolving spatial variability over either T/P and Jason only sampling. It has been shown that the total rms current variability can be estimated by a factor of 1.5 from the average of cross-track rms current values, supporting the results from the near simultaneous tandem data. The spatially averaged shelf-edge transport from combined T/P and Jason observations shows a seasonal cycle with strongest equatorward flow in winter.

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REFERENCES

Benada, R. 1997. Merged GDR (TOPEX/Poseidon) User Handbook, *JPL D-11007*, Jet Propul. Lab., Pasadena, Calif.

Detracey, B.M, Tang, C.L., and Smith, P.C. 1996. Low-frequency currents at the northern shelf edge of the Grand Banks. J. Geophys. Res. 101(C6): 14,223-14,236.

Fratantoni, D.M. 2001. North Atlantic surface circulation during the 1990's observed with satellite-tracked drifters. J. Geophys. Res. 106: 22067-22094.

Han, G. 2003. Circulation over the Newfoundland and Labrador Shelf: a modelling study. *In:* Program and Abstracts, 37th CMOS Congress, Ottawa, p. 164.

2004. TOPEX/Poseidon–Jason comparison and combination off Nova Scotia. Marine Geodesy. 27: 577-595.

Han, G., and Li, J. 2003. Sea surface height and current variability on the Newfoundland Slope from TOPEX/Poseidon altimetry. Can. Tech. Rep. Hydrogr. Ocean Sci. 234: viii + 40 p.

Han, G., and Tang, C.L. 1999. Velocity and transport of the Labrador Current determined from altimetric, hydrographic, and wind data. J. Geophys. Res. 104: 18047-18057.

2001. Interannual variation of volume transport in the western Labrador Sea based on TOPEX/Poseidon and WOCE data. J. Phys. Oceanogr. 31: 199-211.

Han, G., and Wang, Z. 2005. Seasonal-mean circulation and hydrography over the Newfoundland and Labrador Shelf and Slope: a modelling study. In preparation.

Han, G., Tang, C.L., and Smith, P.C. 2002. Annual variations of sea surface elevations and currents over the Scotian Shelf and Slope. J. Phys. Oceanogr. 32: 1794-1810.

Hannah, C.G., Greenberg, D.A., Loder, J.W., and Xu, Z. 1995. Seasonal baroclinic circulation in the Scotia-Maine and Grand Banks regions. *In:* PERD Workshop on Coastal Current Models for Continental Shelves. Edited by W.R. Foreman and M.G.G. Foreman. Kelowna, B.C., June 12, 1995. Can Tech. Rep. Hydrogr. Ocean Sci. No. 169, p. 81-85.

Loder, J.W., Petrie, B.D., and Gawarkiewicz, G. 1998. The coastal ocean off northeastern North America: a large-scale view. Ch. 5. *In* The Global Coastal Ocean: Regional Studies and Synthesis. The Sea, Vol. 11. Edited by K.H. Brink and A.R. Robinson. John Wiley & Sons Inc., pp. 105-133.

Pepin, P., and Helbig, J.A. 1997. Distribution and drift of cod eggs and larvae on the northeastern Newfoundland Shelf. Can. J. Fish. Aquat. Sci. 54: 70-685.

Petrie, B., and Anderson, C. 1983. Circulation on the Newfoundland continental shelf. Atmosphere-Ocean. 21: 207-226.

Ray, R. 1999. A global ocean tide model from Topex/Poseidon altimetry: GOT99.2, NASA Tech Memo 209478, 58 pages, Sept. 1999.

Table 1. T/P rms values (cm/s) at crossovers for cross-track (d-rms for the descending track and a-rms for ascending track) and total current anomalies and the ratios (d/t and a/t) of the former to the latter for the near simultaneous tandem period (January-July, 2002). The average of d/t and a/t at each crossover is given as mdat. The reciprocals of d/t and a/t are expressed as t/d and t/a. 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 (rmma) are also given. SD: Standard Deviation.

Location	d-rms	a-rms	t-rms	t/d	t/a	d/t	a/t	mdat	angle	major	minor	rmma
A(-55.3,46.2)	13.4	16.4	21.7	1.61	1.32	0.62	0.76	0.69	-10.0	19.4	11.0	0.57
B(-53.9,44.7)	12.7	12.7	21.1	1.66	1.66	0.60	0.60	0.60	-0.0	21.4	3.9	0.18
C(-52.4,43.0)	29.3	29.3	47.5	1.62	1.62	0.62	0.62	0.62	-0.0	47.2	13.1	0.28
D(-51.0,41.2)	21.2	25.6	34.2	1.62	1.34	0.62	0.75	0.68	-6.5	32.0	14.8	0.46
E(-52.4,46.2)	11.1	7.2	13.7	1.23	1.91	0.81	0.52	0.67	17.1	12.7	6.00	0.47
F(-51.0,44.7)	10.8	9.4	12.7	1.18	1.35	0.85	0.74	0.79	50.6	9.9	8.5	0.86
G(-49.6,43.0)	15.9	9.6	19.6	1.23	2.05	0.81	0.49	0.65	14.4	18.9	7.1	0.38
H(-48.2,41.2)	24.4	24.8	39.5	1.62	1.60	0.62	0.63	0.62	-0.4	39.1	11.3	0.29
I(-52.4,49.0)	12.5	27.6	30.6	2.44	1.11	0.41	0.90	0.66	-31.8	28.9	12.2	0.42
J(-51.0,47.7)	11.7	5.2	12.6	1.08	2.42	0.93	0.41	0.67	35.7	12.0	5.1	0.43
K(-49.6,46.2)	15.7	6.9	16.8	1.07	2.45	0.93	0.41	0.67	32.1	16.1	6.5	0.40
L(-48.2,44.7)	11.9	9.7	16.2	1.36	1.67	0.73	0.60	0.67	7.2	15.1	7.0	0.46
M(-46.8,43.0)	28.2	21.7	39.0	1.38	1.80	0.72	0.56	0.64	6.9	37.8	13.5	0.36
N(-51.0,50.3)	14.3	15.1	20.7	1.45	1.37	0.69	0.73	0.71	-11.3	16.0	14.0	0.88
O(-49.6,49.0)	22.8	15.4	27.7	1.22	1.80	0.82	0.56	0.69	24.6	24.5	14.7	0.60
P(-48.2,47.7)	14.9	10.6	18.7	1.26	1.77	0.80	0.57	0.68	16.8	16.9	9.2	0.55
Q(-46.8,46.2)	13.8	7.8	14.9	1.08	1.91	0.93	0.52	0.72	40.1	13.5	7.2	0.53
R(-45.4,44.7)	18.9	21.8	30.3	1.60	1.39	0.62	0.72	0.67	-5.3	28.2	13.6	0.48
S(-49.6,51.4)	11.1	11.9	16.4	1.47	1.37	0.68	0.73	0.70	-9.9	13.1	10.6	0.81
T(-48.2,50.3)	9.0	12.2	15.6	1.72	1.27	0.58	0.79	0.68	-16.7	13.9	8.0	0.57
U(-46.8,49.0)	7.8	13.4	16.2	2.07	1.21	0.48	0.82	0.65	-18.3	15.5	6.3	0.40
V(-45.3,47.7)	12.7	10.5	15.1	1.19	1.44	0.84	0.69	0.77	66.2	12.5	9.3	0.74
W(-43.9,46.2)	24.7	26.0	39.0	1.58	1.50	0.63	0.67	0.65	-1.5	37.4	14.8	0.40
Mean					1.47	1.62	0.71	0.64	0.68			0.50
SD					0.33	0.36	0.14	0.13	0.04			0.18
Min.					1.07	1.11	0.41	0.41	0.60			0.18
Max.					2.44	2.45	0.93	0.90	0.79			0.88

Table 2. Same as Table 1, but for Jason.

Location	d-rms	a-rms	t-rms	t/d	t/a	d/t	a/t	mdat	angle	major	minor	rmma
A(-55.3,46.2)	9.6	11.5	15.5	1.62	1.35	0.62	0.74	0.68	-0.7	10.8	7.4	0.68
B(-53.9,44.7)	10.6	12.6	17.7	1.66	1.40	0.60	0.71	0.66	4.9	16.4	7.1	0.43
C(-52.4,43.0)	30.1	29.5	46.7	1.55	1.58	0.64	0.63	0.64	0.8	44.9	16.0	0.35
D(-51.0,41.2)	21.0	21.2	31.7	1.51	1.50	0.66	0.67	0.66	-1.3	20.0	12.6	0.63
E(-52.4,46.2)	21.2	6.7	23.0	1.09	3.44	0.92	0.29	0.61	25.4	22.7	5.1	0.22
F(-51.0,44.7)	12.8	13.5	19.1	1.49	1.42	0.67	0.71	0.69	-8.3	14.4	9.3	0.65
G(-49.6,43.0)	20.6	13.5	27.7	1.35	2.05	0.74	0.49	0.62	9.8	27.3	7.3	0.27
H(-48.2,41.2)	25.0	26.7	39.5	1.58	1.48	0.63	0.68	0.65	-1.7	38.0	13.6	0.36
I(-52.4,49.0)	28.0	21.7	37.7	1.35	1.74	0.74	0.58	0.66	9.8	34.7	14.5	0.42
J(-51.0,47.7)	15.4	8.4	17.6	1.14	2.09	0.88	0.48	0.68	31.0	14.9	7.9	0.54
K(-49.6,46.2)	16.5	6.5	17.5	1.06	2.68	0.94	0.37	0.66	28.0	15.0	5.9	0.39
L(-48.2,44.7)	13.8	11.0	17.6	1.27	1.59	0.79	0.63	0.71	23.7	13.9	8.6	0.62
M(-46.8,43.0)	27.5	19.3	34.4	1.25	1.79	0.80	0.56	0.68	12.8	31.0	15.0	0.49
N(-51.0,50.3)	20.0	14.1	23.8	1.19	1.69	0.84	0.59	0.72	52.9	20.3	11.9	0.59
O(-49.6,49.0)	26.1	23.7	34.5	1.32	1.46	0.76	0.69	0.72	26.0	26.8	20.0	0.75
P(-48.2,47.7)	15.9	9.2	17.4	1.10	1.89	0.91	0.53	0.72	44.6	15.6	8.2	0.53
Q(-46.8,46.2)	15.6	9.4	16.4	1.05	1.75	0.96	0.57	0.76	38.8	10.8	7.6	0.70
R(-45.4,44.7)	21.1	27.0	36.0	1.71	1.33	0.59	0.75	0.67	-11.6	33.2	13.7	0.41
S(-49.6,51.4)	20.4	9.7	22.4	1.10	2.31	0.91	0.43	0.67	51.4	19.6	8.0	0.41
T(-48.2,50.3)	12.0	9.4	14.7	1.23	1.57	0.81	0.64	0.73	61.5	12.2	8.9	0.73
U(-46.8,49.0)	12.0	20.6	25.0	2.08	1.21	0.48	0.82	0.65	-19.1	22.8	9.5	0.42
V(-45.3,47.7)	17.7	9.3	20.7	1.17	2.22	0.86	0.45	0.65	21.0	18.8	8.0	0.43
W(-43.9,46.2)	23.6	32.9	42.5	1.80	1.29	0.56	0.78	0.67	-14.0	39.4	17.1	0.44
Mean				1.38	1.78	0.75	0.60	0.68				0.50
SD				0.28	0.52	0.14	0.14	0.04				0.15
Min				1.05	1.21	0.48	0.29	0.61				0.22
Max				2.08	3.44	0.96	0.82	0.76				0.75

Table 3. Winter and spring near-surface transports (Sv, positive equatorward) between the 200- and 3000-m isobaths and from the surface to the 200-m depth for T/P and Jason.

	Winter		Spring	
	T/P	Jason	T/P	Jason
Track NE096	6.04	6.38	6.05	5.82
Track 024	2.69	2.00	3.20	2.36
Track 113	1.56	1.69	1.62	2.06
Track SW096	2.22	1.82	0.09	0.37

Table 4. Same as Table 1 but for T/P and Jason during the interleaved tandem period (September 2002–December 2003). See Fig. 6 for the crossover locations.

Location	d-rms	a-rms	t-rms	t/d	t/a	d/t	a/t	mdat	angle	major	minor	rmma
a(-53.9,44.7)	15.0	13.3	20.9	1.39	1.57	0.72	0.64	0.68	4.6	18.9	9.4	0.50
b(-52.4,43.0)	20.3	26.5	34.8	1.71	1.31	0.58	0.76	0.67	-9.7	31.9	14.2	0.45
c(-52.4,46.2)	13.9	9.3	16.1	1.16	1.73	0.86	0.58	0.72	31.7	13.7	8.6	0.63
d(-51.0,44.7)	13.5	9.7	16.8	1.24	1.73	0.81	0.58	0.69	15.6	14.9	7.8	0.52
e(-49.6,43.0)	23.8	18.8	29.1	1.22	1.54	0.82	0.65	0.73	14.5	24.9	15.4	0.62
f(-52.4,49.0)	17.2	21.1	27.4	1.60	1.30	0.63	0.77	0.70	-15.8	22.9	15.6	0.68
g(-51.0,47.7)	8.9	17.8	20.7	2.33	1.17	0.43	0.86	0.64	-22.0	19.6	7.3	0.37
h(-49.6,46.2)	8.6	7.5	11.4	1.33	1.52	0.75	0.66	0.70	10.1	9.5	6.2	0.65
i(-48.2,44.7)	25.0	12.1	28.6	1.15	2.36	0.87	0.42	0.65	21.5	27.2	9.9	0.36
j(-46.8,43.0)	48.3	32.0	63.9	1.32	1.99	0.76	0.50	0.63	10.5	59.7	19.5	0.33
k(-49.6,49.0)	11.6	14.7	17.9	1.55	1.22	0.65	0.82	0.73	-53.9	14.4	11.0	0.77
l(-48.2,47.7)	13.9	15.7	20.7	1.49	1.32	0.67	0.76	0.71	-8.0	16.6	12.0	0.72
m(-46.8,46.2)	22.8	12.0	25.7	1.12	2.15	0.89	0.47	0.68	27.8	23.5	10.8	0.46
n(-46.8,49.0)	11.0	11.6	15.3	1.38	1.32	0.72	0.76	0.74	-74.6	11.5	9.9	0.86
A(-55.3,44.7)	12.9	9.0	15.8	1.22	1.75	0.82	0.57	0.69	16.7	14.0	7.5	0.54
B(53.9,43.0)	16.3	12.2	21.4	1.31	1.75	0.76	0.57	0.67	9.4	19.8	8.6	0.44
C(-53.9,46.2)	14.3	9.9	18.0	1.26	1.82	0.79	0.55	0.67	14.6	16.4	7.9	0.48
D(-52.4,44.7)	12.5	8.9	14.7	1.17	1.65	0.85	0.61	0.73	24.3	12.5	8.0	0.64
E(-51.0,43.0)	12.2	15.8	20.9	1.70	1.32	0.59	0.76	0.67	-8.8	19.2	8.60	0.45
F(-52.4,47.7)	10.3	19.7	22.5	2.18	1.14	0.46	0.87	0.67	-26.6	20.6	9.40	0.46
G(-51.0,46.2)	8.9	8.8	12.8	1.44	1.46	0.69	0.68	0.69	0.8	11.2	6.5	0.58
H(-49.6,44.7)	9.6	7.6	12.5	1.30	1.66	0.77	0.60	0.68	10.4	11.2	5.9	0.52
I(-48.2,43.0)	26.4	17.9	32.8	1.24	1.83	0.81	0.55	0.68	13.8	30.1	13.7	0.45
J(-51.0,49.0)	14.5	13.8	20.4	1.41	1.48	0.71	0.68	0.69	3.8	17.1	11.3	0.66
K(-49.6,47.7)	13.1	10.1	17.0	1.30	1.68	0.77	0.60	0.68	13.1	14.9	8.4	0.56
L(-48.2,46.2)	10.5	8.5	13.9	1.33	1.63	0.75	0.61	0.68	9.6	12.3	6.7	0.55
M(-46.8,44.7)	21.1	26.4	35.1	1.66	1.33	0.60	0.75	0.68	-8.8	31.8	15.8	0.50
N(-48.2,49.0)	9.0	7.5	11.6	1.30	1.55	0.77	0.65	0.71	19.8	9.3	7.1	0.76
O(-46.8,47.7)	9.0	10.1	13.8	1.53	1.37	0.65	0.73	0.69	-6.8	11.8	7.4	0.62
Aa(-54.6,43.8)	15.6	18.6	24.7	1.58	1.32	0.63	0.75	0.69	-7.8	21.9	11.8	0.54
Bb(-54.6,45.5)	20.2	8.8	22.4	1.11	2.54	0.90	0.39	0.65	25.6	21.1	7.7	0.37
Cc(-53.1,43.8)	13.9	11.6	18.8	1.36	1.61	0.74	0.62	0.68	6.2	17.0	8.3	0.49
Dd(-53.1,45.5)	12.2	12.0	16.3	1.34	1.36	0.75	0.73	0.74	2.2	12.9	10.2	0.79
Ee(-51.7,43.8)	8.4	14.9	18.4	2.19	1.23	0.46	0.81	0.63	-14.7	17.7	5.9	0.33
Ff(-51.7,45.5)	10.3	8.5	12.6	1.22	1.49	0.82	0.67	0.74	23.5	10.1	7.7	0.76
Gg(-50.3,43.8)	11.6	8.1	13.4	1.16	1.66	0.86	0.60	0.73	24.0	11.6	7.1	0.61
Hh(-51.7,47.0)	9.2	9.6	13.2	1.43	1.37	0.70	0.73	0.71	-3.9	10.8	7.8	0.73
Ii(-50.3,45.5)	9.9	8.9	12.4	1.26	1.40	0.80	0.72	0.76	20.5	9.6	8.1	0.84
Jj(-48.9,43.8)	16.5	17.3	22.2	1.35	1.29	0.74	0.78	0.76	-2.6	17.5	13.6	0.78
Mm(-48.9,45.5)	19.9	8.2	21.3	1.07	2.60	0.93	0.38	0.66	29.8	20.2	7.5	0.37
Kk(-51.7,48.4)	14.4	11.6	17.8	1.24	1.54	0.81	0.65	0.73	37.9	14.1	11.1	0.79
Ll(-50.3,47.0)	8.8	8.1	11.7	1.33	1.45	0.75	0.69	0.72	9.0	9.3	7.2	0.77
Nn(-47.5,43.8)	25.3	21.8	34.0	1.35	1.56	0.74	0.64	0.69	6.2	30.2	16.2	0.54

. . . Cont'd.

Table 4. (Cont'd.)

Location	d-rms	a-rms	t-rms	t/d	t/a	d/t	a/t	mdat	angle	major	minor	rmma
Oo(-50.3,48.4)	12.8	13.7	18.0	1.40	1.32	0.71	0.76	0.74	-32.6	13.3	12.4	0.93
Pp(-48.9,47.0)	7.4	12.0	14.1	1.91	1.17	0.52	0.85	0.69	-25.0	12.6	6.8	0.54
Qq(-47.5,45.5)	13.6	16.3	22.5	1.66	1.38	0.60	0.72	0.66	-6.5	20.7	9.5	0.46
Rr(-48.9,48.4)	14.1	10.8	17.9	1.27	1.65	0.79	0.60	0.70	16.4	15.1	9.7	0.64
Ss(-47.5,47.0)	17.5	14.5	21.0	1.20	1.44	0.84	0.69	0.76	56.5	16.6	13.2	0.80
Tt(-47.5,48.4)	10.1	12.1	16.0	1.58	1.32	0.63	0.76	0.69	-12.0	13.6	8.8	0.64
Uu(-46.1,47.0)	10.5	8.3	13.2	1.26	1.59	0.80	0.63	0.71	19.4	11.0	7.5	0.68
Vv(-46.1,48.4)	13.9	12.1	18.6	1.34	1.54	0.75	0.65	0.70	10.7	15.5	10.6	0.69
Mean				1.41	1.56	0.73	0.66	0.70				0.59
SD				0.27	0.32	0.11	0.11	0.03				0.15
Min				1.07	1.14	0.43	0.38	0.6				0.33
Max				2.33	2.60	0.93	0.87	0.76				0.93

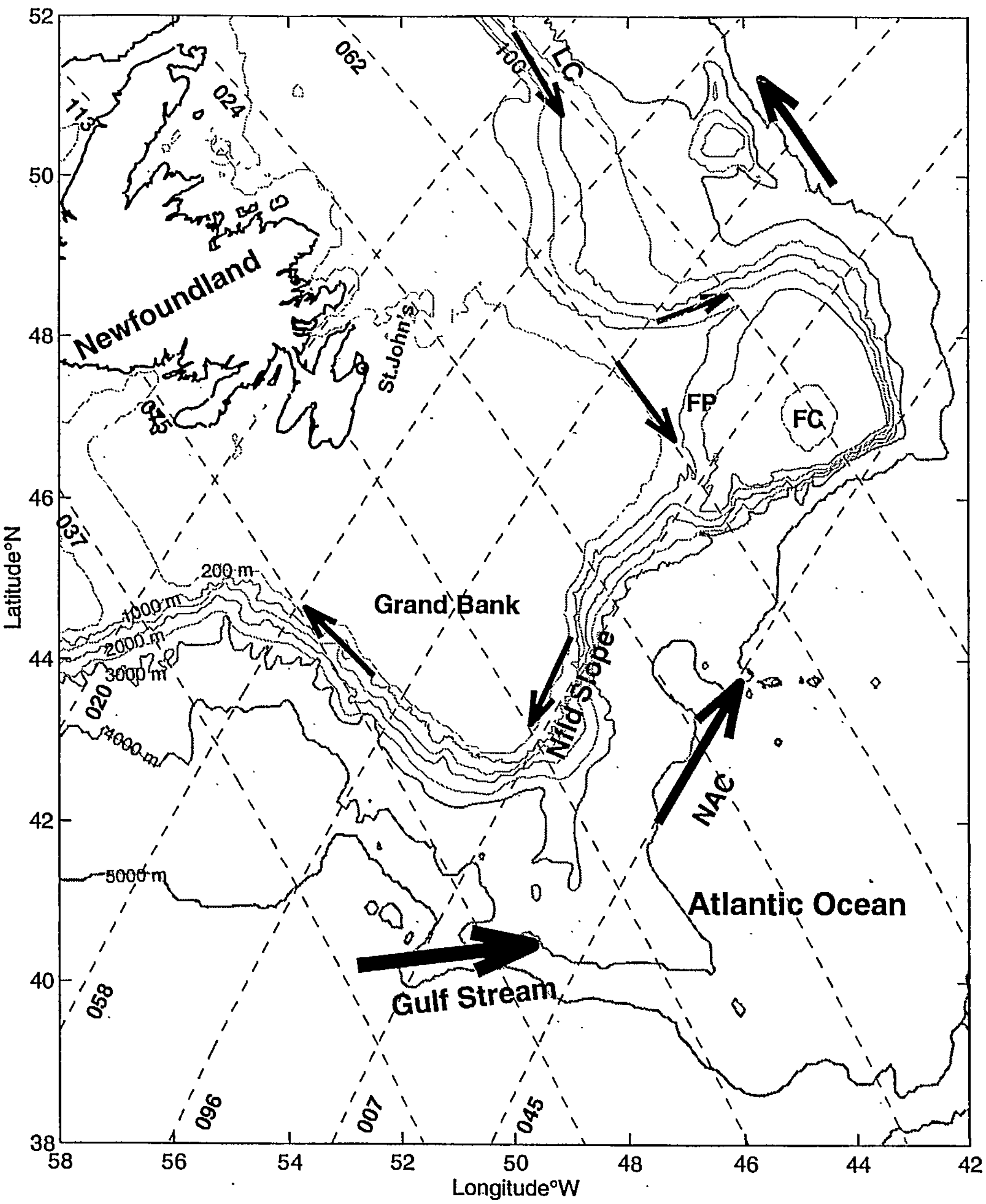

Figure 1. Map showing the Newfoundland Shelf, Slope and adjacent deep waters with a schematic representation of the circulation. The labeled dash lines are the selected T/P and Jason ground tracks during the T/P and Jason near simultaneous tandem period (January-July 2002). FC: Flemish Cap; FP: Flemish Pass; LC: Labrador Current.

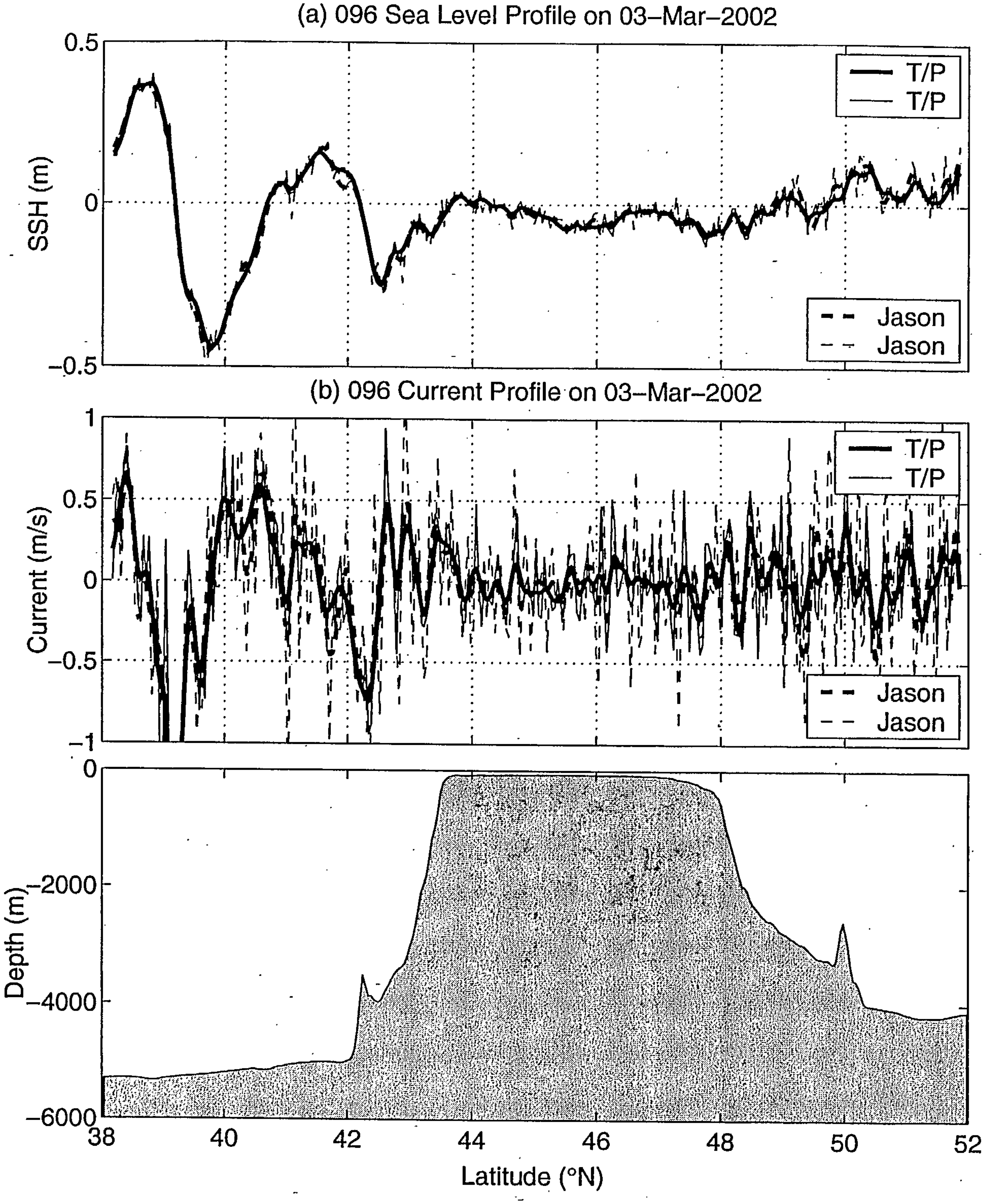

Figure 2. (a) Along-track profiles of T/P and Jason sea surface height anomalies for Track 096 (see Fig.1 for location) on March 03, 2002: unsmoothed (thin line) vs. smoothed with the digital filter (thick line). (b) Associated cross-track geostrophic current anomalies (positive northwestward). The bottom topography is shown in the lower panel.

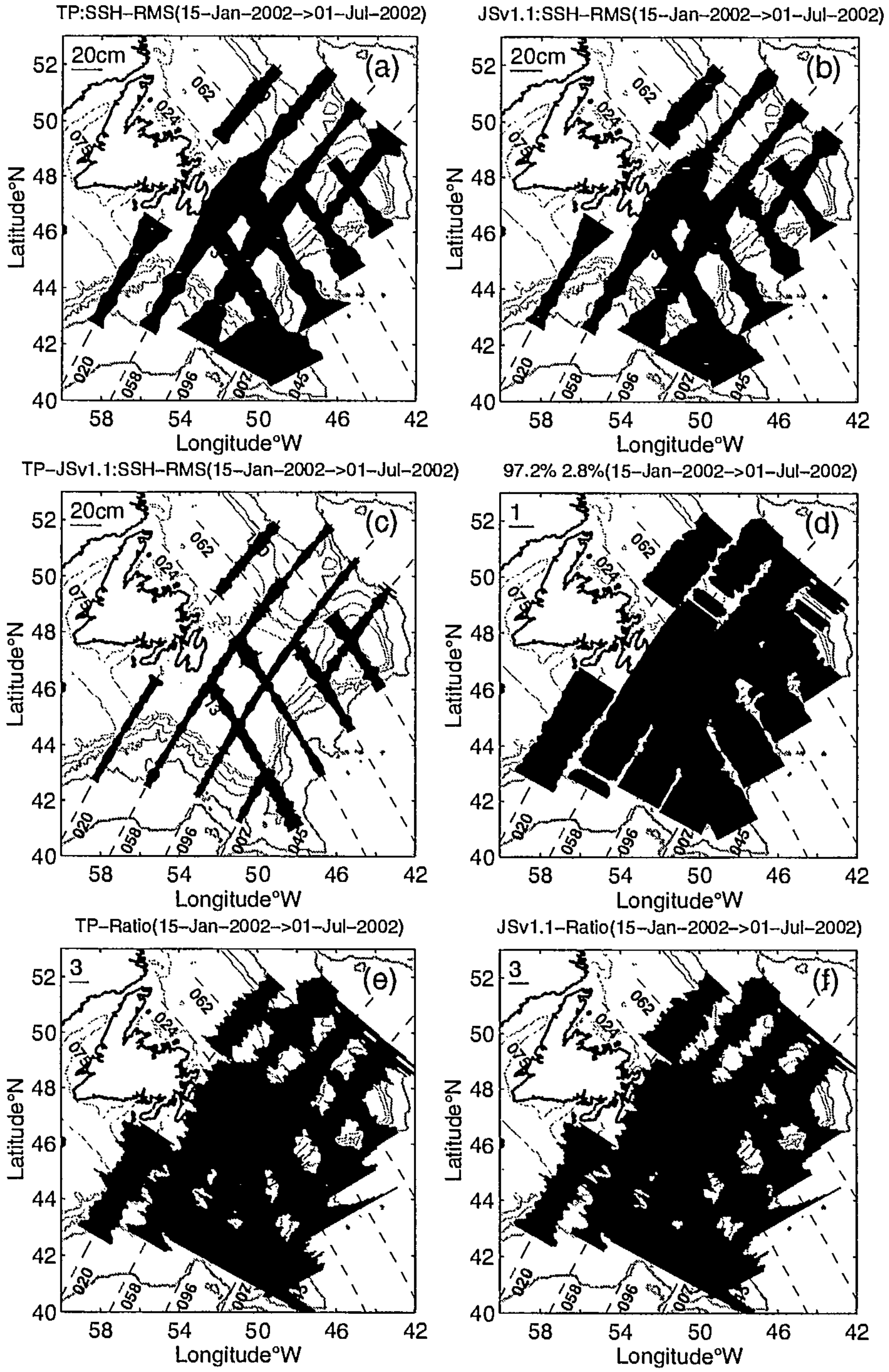

Figure 3. (a) Twice the T/P rms sea level variability; (b) Same as (a) but for Jason; (c) Twice the rms difference between T/P and Jason, (d) T/P and Jason correlation coefficient (shown only if different from zero at the 5% significance level), (e) Twice the square root of T/P signal-to-noise variance ratio, and (f) Same as (e) but for Jason during the near simultaneous tandem period.

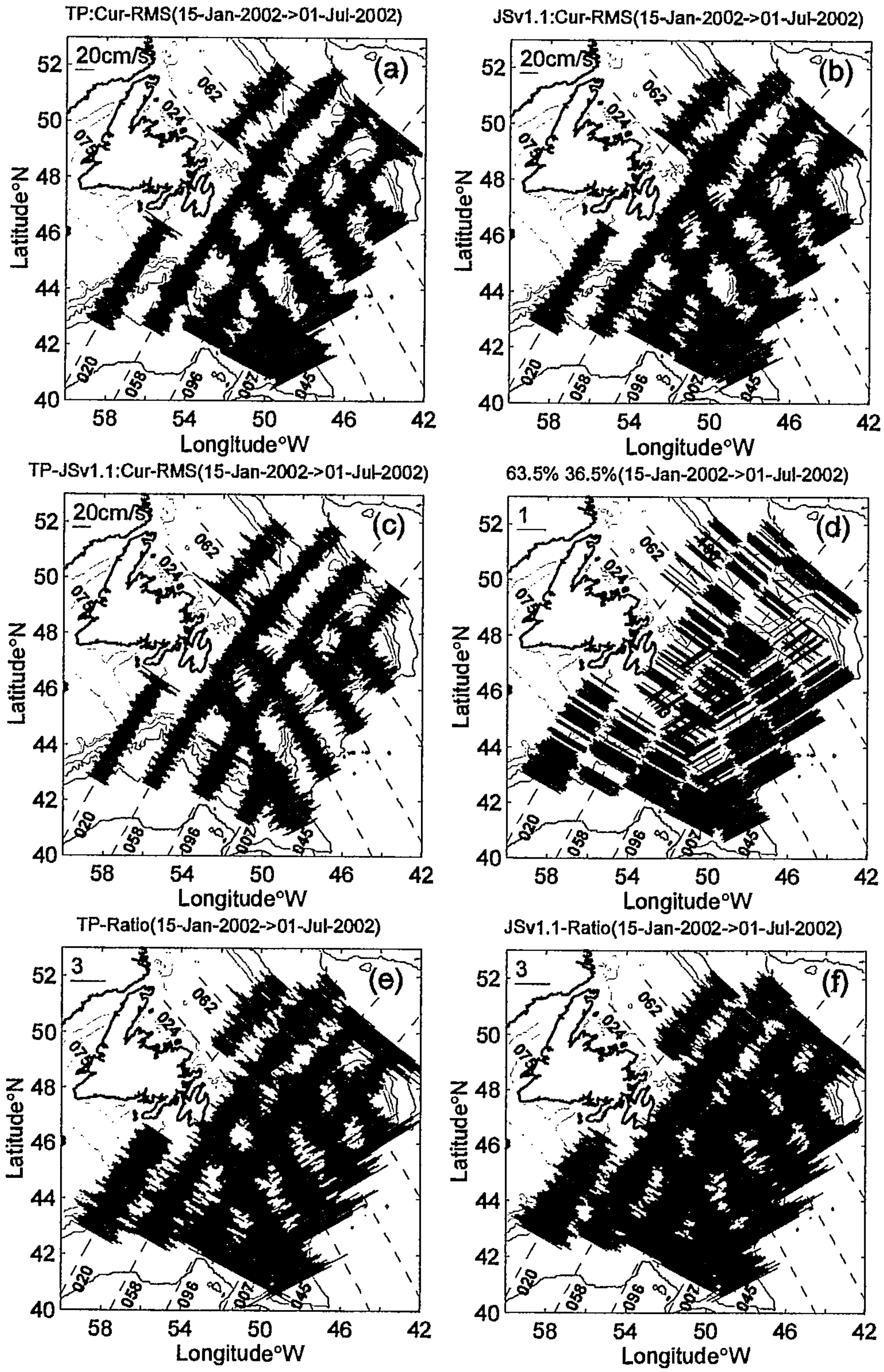

Figure 4. Same as Fig. 3 but for cross-track surface current anomalies.

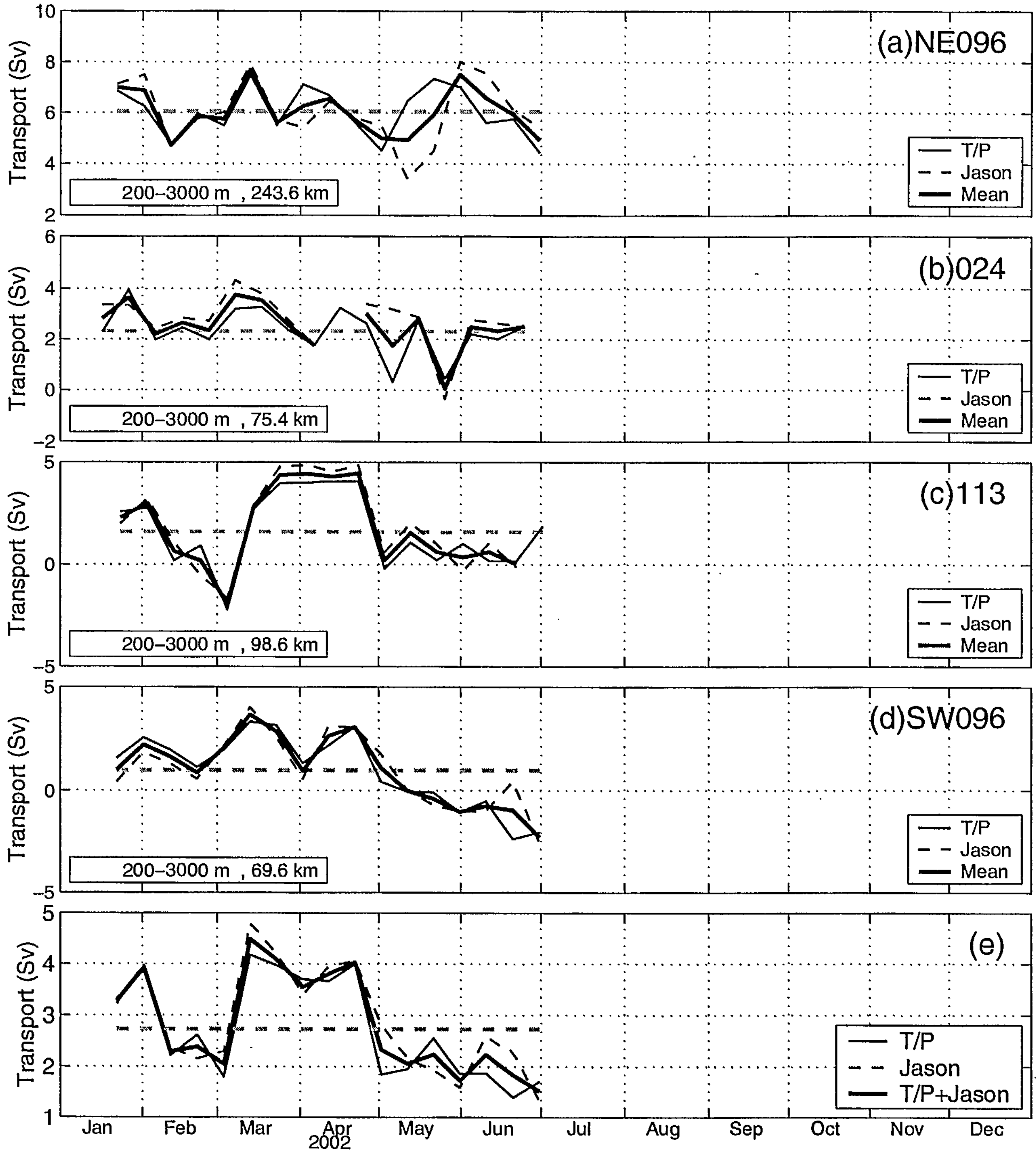

Figure 5. Total volume transport from the sum of the T/P and Jason altimetric anomalies and Han's (2003) model annual mean between the 200- to 2000-m isobath and from the surface to the 200-m depth during the near simultaneous tandem period, positive southwestward. (a) Track NE096, (b) Track 024, (c) Track 113, (d) Track SW096, and (e) The four-track average. The grey dashed line depicts the model annual mean. See Fig. 1 for track locations.

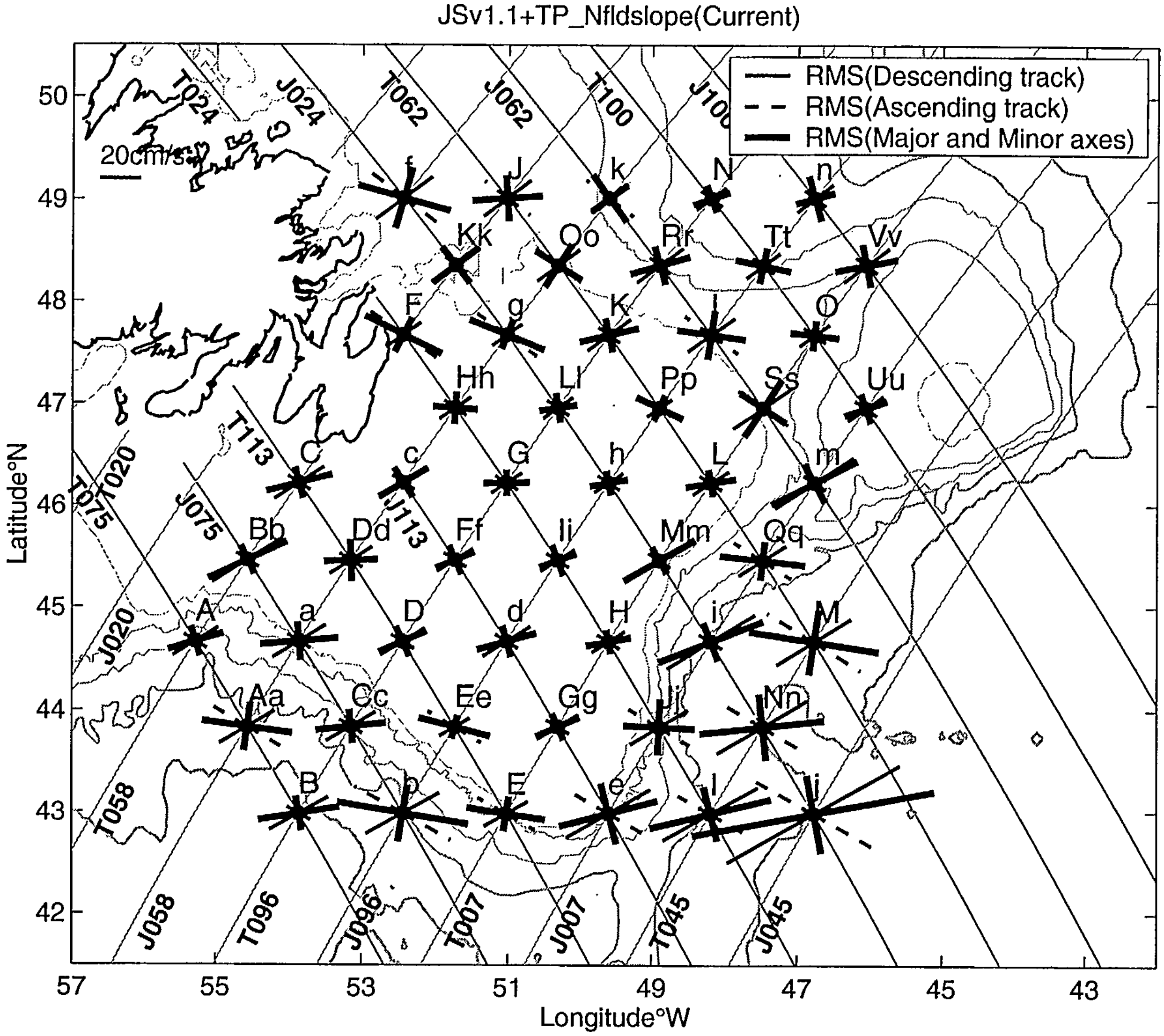

Figure 6. Twice the rms current variability at crossovers during the interleaved tandem period. The T/P and Jason tracks are identified as T and J leading the numeric numbers, respectively. Upper-case letters: T/P crossovers; Lower-case letters: Jason crossovers; Upper-and lower-case letters: T/P-Jason crossovers.

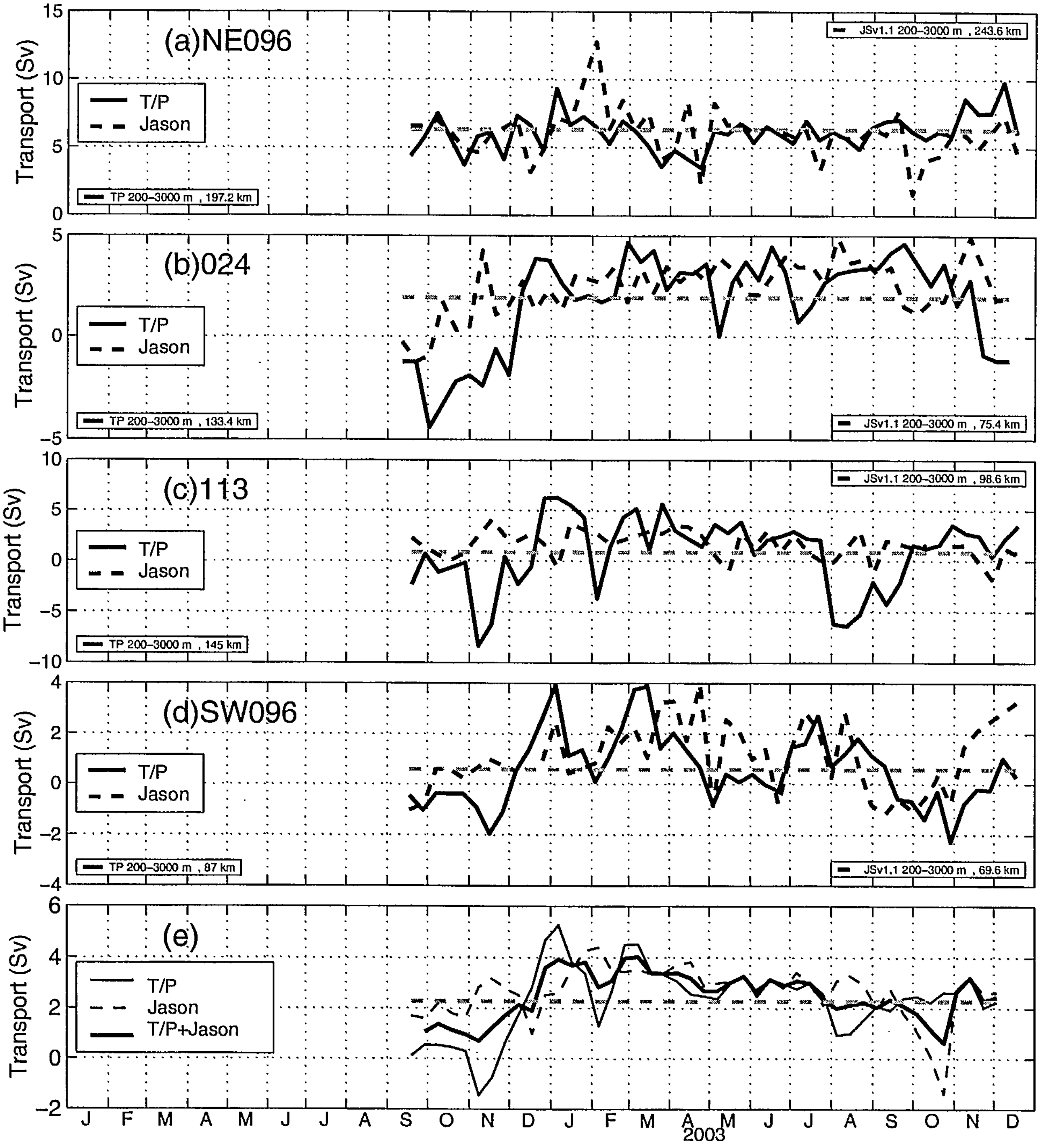

Figure 7. Total volume transport from the sum of the T/P and Jason altimetric anomalies and Han's (2003) model annual mean between the 200- to 2000-m isobath and from the surface to the 200-m depth during the interleaved tandem period, positive southwestward. (a) Track NE096, (b) Track 024, (c) Track 113, (d) Track SW096, and (e) The four-track average. The grey dashed line depicts the model annual-mean. See Fig. 6 for track locations.