GEO-REFERENCED SEA SURFACE TOPOGRAPHY FOR THE SCOTIAN SHELF FROM SATELLITE ALTIMETRY

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Geo-Referenced Sea Surface Topography for the Scotian Shelf from Satellite Altimetry

by

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ABSTRACT

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Altimetry data from the TOPEX/Poseidon (T/P) mission are used to provide geo-referenced seasonal-mean sea surface topography for the Scotian Shelf and Slope, and the approaches to the Bay of Fundy during the period 1992 to 2002. The T/P data are also used to estimate seasonal-mean sea level along the Nova Scotia coast. Comparisons with sea level measurements from coastal tide gauges are carried out to evaluate the potential of altimetry data for coastal sea level monitoring. Eight major diurnal and semi-diurnal tidal constituents are derived from an older version of T/P data in which tidal signals have not been removed. The present altimetric tides agree generally with *in situ* observations, but with notable discrepancies for some constituents at some coastal sites. A prediction tool using the T/P-derived tidal constituents is implemented to forecast tidal levels for the Scotian Shelf and at Yarmouth, Halifax and North Sydney. The resulting fields are presented online (http://sultry.nfl.dfo-mpo.gc.ca/internet_site/english/guoqi/topex_scotian_shelf.htm) and are available to research and coastal communities.

RÉSUMÉ

Guoqi Han, John Loder, Brian Petrie, Jianyong Li, and Charles O'Reilly. 2004. Geo-Referenced Sea Surface Topography for the Scotian Shelf from Satellite Altimetry. Can. Tech. Rep. Hydrogr. Ocean Sci. 237: vi + 29 p.

Les données altimétriques obtenues dans le cadre de la mission TOPEX/Poseidon (T/P) sont utilisées pour fournir des moyennes saisonnières de la topographie géoréférencée de la surface de la mer pour la région de la plate-forme et du talus néo-écossais, ainsi que pour les abords de la baie de Fundy, au cours de la période 1992 à 2002. Les données T/P servent également à estimer les moyennes saisonnières du niveau de la mer, le long de la côte de la Nouvelle-Écosse. Des comparaisons avec des mesures du niveau de la mer, relevées par des marégraphes, permettent d'évaluer le potentiel des données altimétriques en matière de surveillance du niveau de la mer le long du littoral. Huit composantes diurnes et semi-diurnes importantes de la marée sont dérivées d'une version plus ancienne de données T/P dont on n'a pas retiré les signaux de marée. Les données altimétriques actuelles sur les marées concordent généralement avec les observations *in situ*, mais présentent des différences notables pour certaines composantes à certains sites côtiers. Un outil de prévision utilisant des composantes de la marée dérivées des données T/P est mis en œuvre afin de prévoir les niveaux des marées pour la plate-forme néo-écossaise, ainsi qu'à Yarmouth, Halifax et North Sydney. Les champs qui en résultent sont présentés en ligne (http://sultry.nfl.dfo-mpo.gc.ca/internet_site/english/guoqi/topex_scotian_shelf.htm) et sont à la disposition des chercheurs et des collectivités côtières.

1. Introduction

Satellite altimetry provides reliable measurements of offshore sea level variations, particularly large amplitude variations such as associated with tides (Han et al., 1996), major currents and ocean eddies (Han, 2002). Estimation of associated sea level variations at coastal sites from altimetry is more challenging because of data degradation and sparsity near land. Nevertheless there is high potential that altimetry can contribute to coastal sea level monitoring, particularly in areas with spatially-varying sea level changes and in remote areas. The altimetry data of near-decade length now available from the T/P mission allow an extraction of important seasonal and interannual variations in sea level which are of significance to coastline variability, climate and other societal issues in Atlantic Canada.

In this report we used T/P altimetry data for the period from 1992-2002 to study sea level variability over the Scotian Shelf. Our objectives are: 1) to provide geo-referenced seasonal-mean sea surface topography over the Scotian Shelf and adjacent regions by season and year, 2) to compare estimates of mean and seasonal/interannual variations in coastal sea level from T/P altimetry with those from GPS-positioned tide gauge data at selected sites along the Nova Scotia coast, in order to evaluate the potential of satellite altimetry for coastal sea level monitoring, and 3) to provide improved observational estimates of the tidal variations in sea surface topography over the Scotian Shelf. The results should be useful to research and coastal communities in various applications such as interpreting remote-sensing and other data, improving bathymetric chart datums, and evaluating implications of climate change for coastal areas of Atlantic Canada.

This report consists of four sections. Section 2 briefly describes data sets and processing techniques. Section 3 presents results and a summary is given in section 4.

2. Methodology

2.1 T/P data and processing for seasonal means

T/P sea-surface height data for the period from mid 1992 to May 2002 obtained from the NASA Pathfinder Project are used to study seasonal-mean sea surface height variability. The satellite has a nominal repeat cycle of 10 days, and ideally there are 360 observations at each location. There are ascending (SW-NE) and descending (NW-SE) tracks with spacing of about 200 km on the Scotian Shelf (Fig. 1). 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, including:

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) ocean, load, solid Earth and pole tides.

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

An along-track digital filter with a filter width of about 36 km (7 points) is applied to the altimetric sea surface height data. The results presented are based on the smoothed height data unless indicated otherwise. A time-mean sea surface was constructed from the T/P data. We then calculate the sea surface height anomalies relative to the mean sea surface. Both the marine geoid and mean oceanic topography are removed by this procedure.

2.2 T/P data and tidal analysis

The T/P data used for tidal analysis are essentially the same, except for duration and some of the geophysical corrections applied. The data period is from August 1992 to December 2001. There were no ocean, load and pole tide corrections, but the inverse barometric response of sea surface height to atmospheric pressure change was applied to the data. These data are henceforth called the tide-in T/P data.

A response analysis method (Han et al., 1996) was used to extract eight major tide constituents from the tide-in T/P data. A tidal prediction tool was implemented to forecast tidal levels based on the altimetric tidal information.

2.3 Tide-gauge data and processing

Water level data at three permanent tide-gauge sites along the Nova Scotia coast (North Sydney, Halifax and Yarmouth) were obtained from Marine Environmental Data Service (MEDS) of Fisheries and Oceans Canada. One-hour water level records are quality controlled, detided using the Godin 25_24_24 filter and averaged to produce monthly mean sea levels. The 2002 data from North Sydney were suspect and not included in this analysis. The 2002 data for the two other sites received no or only minimal quality control by MEDS but appeared to be of good quality.

3. Results

3.1 Altimetric mean surface topography

Mean sea levels at T/P track locations were calculated over the period from 1992 to 2002 relative to the T/P ellipsoid. We also bi-linearly interpolated the 2' by 2' GSFC00 mean surface topography (Wang, 2001) onto the track locations. The differences between the T/P and GSFC00 mean sea levels (the former minus the latter) were computed location by location. We then mapped the differences onto a 0.2° by 0.2° grid using an optimal linear interpolation method

(Hendry and He, 2004) with a correlation scale of 3° and 3° in the longitudinal and latitudinal directions. The mapped differences were added onto the GSFC00 mean sea surface. Fig. 2 presents the T/P mean sea surface topography averaged over the period from 1992 to 2002.

3.2 Altimetric seasonal-mean sea-surface topography anomalies

Fig. 3 shows long-term seasonal-mean sea-surface topography anomalies averaged from 1992 to 2002. They were constructed using the optimal linear interpolation method. We can see the coastal sea level is highest in fall except for winter west of Halifax and lowest in spring. Over the open shelf the sea level is highest in late summer and fall and lowest in early spring. The seasonal variability is enhanced over the continental slope, presumably associated with shifting and/or meandering of the Gulf Stream and rings pinched off from it. The annual sea level range varies from 10 cm near the coast to 20 cm over the lower slope. The present results extend and expand an earlier study of Han et al. (2002). Relatively low sea level nearshore in summer is probably associated with coastal upwelling under alongshore wind forcing and relatively high sea level off the southwestern Nova Scotia in winter may be associated with the passage of the peak Nova Scotian Current (Han et al., 1997).

Fig. 4 presents seasonal-mean sea-surface topography anomalies by season for selected years, constructed using the linear interpolation method. In addition to seasonal variations, we also see significant interannual fluctuations. The sea level over the Scotian Shelf was low around 1994, highest in 1996/97, close to normal in the late 1990s (Han, 2002). The interannual variability over the Scotian Slope is out of phase with that over the Scotian Shelf. See http://sultry.nfl.dfo-mpo.gc.ca/internet_site/english/guoqi/topex.html for seasonal-mean sea-surface topography anomalies for the entire period.

3.3 Seasonal and interannual sea level anomalies at tide-gauge stations and offshore

An important aspect of this report is to evaluate accuracy of altimetic estimates of coastal sea levels. Fig. 5 presents seasonal-mean sea level estimates at selected tide-gauge sites along the Nova Scotia coast, extrapolated from the altimetry data using the aforementioned optimal linear interpolation method. There are significant interannual variations at all the sites. In general, the sea level was low in the early 1990s, high in mid 1990s and close to normal in the late 1990s and early 2000s. The range is about 10 cm.

Fig. 6 compares altimetric estimates with tide-gauge measurements at three permanent tide-gauge sites (North Sydney, Halifax and Yarmouth). The correlation coefficients are 0.53-0.64. The root-mean-square (RMS) differences are 3.5-4.5 cm, comparable to the RMS values. The removal of the annual and semiannual cycles significantly enhances the agreement at Halifax (the RMS difference: 1.5 cm), and slightly less so at the other two sites (the RMS difference: 2.3, 1.9 cm) (Fig. 7). There also appears to be some systematic difference between the tide gauge and satellite observations, i.e., for the first half of the record the difference (satellite minus gauge) is generally negative, for the second half mostly positive at all 3 sites. Lowest correlation and largest RMS difference at North Sydney are consistent with poorest T/P coverage for this site.

To provide further information on the along-shelf and cross-shelf structure of sea level anomalies, four along-track bands were selected based on bathymetry: (i) coast to mid-shelf, (ii) mid-shelf to 200 m, (iii) 200-2000m and (iv) 2000-4000m. For Tracks 050, 088 and 126, we average sea level anomalies band by band every cycle. Fig. 8 presents time series of the averaged sea level anomalies. Least squares fit is carried out to derive the annual cycle from the sea level anomalies (Table 1).

Table 1. Annual cycles of sea level derived from the segment-averaged T/P data. Amplitudes are in metres and phases indicate the year day at the maximum sea level.

	050		088		126	
Segment	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
Shore to Mid-shelf	0.037	8	0.049	314	0.035	290
Mid-shelf to 200-m	0.013	343	0.052	300	0.050	297
200-m to 2000-m	0.046	252	0.055	272	0.048	280
2000-m to 3000-m	0.052	266	0.063	275	0.071	264

Table 2. The RMS values (m) of (a) the raw 10-d sea level data, (b) with the annual cycle removed, and (c) with an additional 37-point moving filter applied.

	050			088			126		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
Shore to Mid-shelf	0.118	0.115	0.022	0.116	0.110	0.028	0.108	0.104	0.030
Mid-shelf to 200-m	0.097	0.097	0.014	0.107	0.100	0.021	0.113	0.106	0.032
200-m to 2000-m	0.107	0.101	0.019	0.114	0.107	0.027	0.109	0.104	0.029
2000-m to 3000-m	0.125	0.119	0.040	0.127	0.118	0.037	0.117	0.105	0.024

Over the inner shelf, the amplitude of the annual cycle is about 5 cm, decreasing towards both the northeastern and southwestern ends of shelf (Table 1). The phase pattern shows a ~2 month lag from east to west, suggesting a southwestward propagation of the sea level signal. The amplitude of the annual cycle is larger over the continental slope. The sea level is highest in September/October, probably mainly associated with steric effects due to thermal expansion of the upper ocean in response to the surface heating and cooling. The outer Scotian Shelf and the shelf edge show transitional features between those of the slope and the inner shelf.

The RMS sea level values (Table 2) indicate the higher-frequency variability dominates over the annual and interannual cycles over the Scotian Shelf Slope, as can be seen from Fig. 8. Off the central and western Nova Scotia, the interannual variability increases notably towards the deep ocean (Table 2).

3.4 Major tidal constituents

We have derived eight major semi-diurnal (M_2, S_2, N_2, K_2) and diurnal (K_1, O_1, P_1, Q_1) tidal constituents from the tide-in T/P data using a response analysis method. The altimetric tides on the ascending and descending tracks are interpolated/extrapolated onto a 0.2° by 0.2° grid using an optimal linear interpolation method (Hendry and He, 2004) with a correlation scale of 3° and 3° in the longitudinal and latitudinal directions. Fig. 9 presents amplitudes and Greenwich phase lags of M2, S2, N2, K_1 and O1. The major features are consistent with previous results (e.g. Han et al., 1996). For example, the semidiurnal has small amplitude and phase change from the east to west, except for the southwestern Scotian Shelf. The diurnal features amphidromic points near the eastern Scotian Shelf.

We have compared the present altimetry estimates with *in situ* observations from coastal tide gauges at the 3 permanent tide-gauge stations (Table 3). For Halifax and North Sydney, the same optimal linear interpolation method (Hendry and He, 2004) is used to produce the altimetric estimates. For Yarmouth, a linear extrapolation scheme is used, with the altimetric tidal data on Track 033 only.

Table 3. Harmonic constants from T/P estimates and tide-gauge observations (in braces) for the 8 major semi-diurnal and diurnal constituents at North Sydney, Halifax and Yarmouth. Amplitudes are in meters and Greenwich phase lags are in degrees.

	Yarmouth		Halifax		North Sydney	
	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
M2	1.658(1.652)	62(61)	0.584 (0.633)	349(351)	0.368(0.510)	353(349)
S2	0.272(0.287)	96(89)	0.139 (0.139)	17(23)	0.109(0.143)	37(24)
N2	0.351(0.336)	34(35)	0.139 (0.14)	333(327)	0.076(0.106)	330(320)
K2	0.082(0.059)	98(90)	0.035 (0.039)	19(16)	0.03(0.035)	32(27)
K1	0.14(0.137)	183(183)	0.088 (0.109)	123(123)	0.077(0.043)	325(27)
O1	0.108(0.124)	165(169)	0.018 (0.04)	127(94)	0.082(0.029)	287(332)
P1	0.048(0.050)	182(183)	0.024(0.032)	122(124)	0.026(0.015)	315(29)
Q1	0.016(0.019)	160(124)	0.014(0.006)	128(335)	0.011(0.012)	250(286)

There is good agreement between tide-gauge data and T/P estimates at Yarmouth. This is mainly due to Track 033 closely passes by Yarmouth. The largest amplitude (phase) difference is 0.023 m (36°) with RMS differences over 8 constituents of 0.012 m (9°).

At Halifax, M2 is low by about 0.04 m, S2 and N2 are within 0.001 m. K1 and O1 are low by about 0.01 and 0.02 m. There is generally good agreement in phase except for O1.

At North Sydney, the altimetric tide is high by 0.14 m for M2, low by 0.03 m for S2 and N2 and high by 0.04 and 0.05 m for K1 and O1. There are also larger phase differences at this site than at Yarmouth or Halifax. As we can see, the nearest altimetric data points are far from North Sydney. For the diurnals, the presence of amphydromic points further limits the accuracy of extrapolation of altimetric tides onto the coastal site.

The altimetric tidal results are also evaluated against other coastal tide-gauge data and pelagic bottom pressure gauge measurements (see Fig. 10). A comparison of the present altimetric tide solutions with Han et al.'s (1996) altimetric estimates indicates overall improvement for the diurnal tides (Table 4). The nearly doubled record length is now sufficient to get the aliased K1 tide (which has an aliasing period of 172.3 d) separated from the semi-annual cycle, which improves the estimation of the tidal admittance at each frequency of the diurnal species.

Table 4. The RMS differences between the altimetric tides and in situ observations. The values in braces are from Han et al.'s (1996) solutions. Amplitudes are in meters and phases are in degrees.

	Coastal		Pelagic	
	Amplitude	Phase	Amplitude	Phase
M2	0.031 (0.040)	11 (7)	0.012 (0.008)	4 (4)
S2	0.017 (0.031)	13 (15)	0.015 (0.016)	10 (9)
N2	0.014 (0.015)	17 (17)	0.012 (0.009)	8 (8)
K1	0.014 (0.017)	15 (48)	0.013 (0.014)	10 (17)
O1	0.019 (0.031)	29 (69)	0.018 (0.017)	21 (28)

A tidal prediction tool is implemented for the Scotian Shelf based on the harmonic constants for the eight tidal constituents. The 24-h forecast results are presented online and updated daily (http://sultry.nfl.dfo-mpo.gc.ca/internet_site/english/guoqi/topex.html). A comparison of predicted tidal levels from the 8 tidal constituents using altimetry and tide-gauge analysis respectively is made at the three permanent tide-gauge sites (Fig. 11), showing good agreement at Yarmouth and Halifax, and large discrepancies at North Sydney. For the time period considered, the RMS difference from the hourly prediction is 1.5, 3.2 and 16.2 cm for Yarmouth, Halifax and North Sydney.

4. Summary

We have derived seasonal–mean sea levels and major tidal constituents over the Scotian Shelf from T/P data. The sea level along the coast is highest in fall and lowest in spring, and over the open shelf, highest in late summer and lowest in early spring. The magnitude increases over the Scotian Slope. The sea level over the Scotian shelf was low in the early 1990s, highest in 1996/97, and close to normal in the late 1990s. A comparison of T/P estimates and tide-gauge measurements at the coastal stations indicates fair agreement at seasonal and interannual scales.

Eight major semi-diurnal and diurnal constituents are derived from the tide-in T/P data. Comparison with tide-gauge data and bottom pressure gauge data indicate overall good agreement. The present tidal solutions are in better agreement with tide-gauge data than Han et al.'s (1996) for the K1 and O1 tides, but nearly the same for M2, S2 and N2. Detailed comparisons for the three permanent tide-gauge stations indicate good agreement at Yarmouth and Halifax, but with notable discrepancies at North Sydney.

For estimating coastal sea levels from satellite altimetry, higher spatial resolution is demanded. It is apparent that the close agreement between altimetric estimates and tide-gauge measurements at Yarmouth and Halifax can be partly attributed to better data coverage near the site. The tandem missions of T/P and Jason-1 will provide sea level data with doubled cross-track resolution. It is therefore expected that the coastal sea levels can be improved using the data from the two missions, when combined with those generated from other satellite altimetry missions.

Acknowledgements

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References

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

Han, G., 2002. Interannual sea level variations in the Scotia-Maine region in the 1990s. *Canadian J. of Remote Sensing*, 581-587, 2002.

Han G., M. Ikeda and P.C. Smith, 1996. Oceanic tides on the Newfoundland and Scotian Shelves from TOPEX/POSEIDON altimetry. *Atmosphere-Ocean*, 34(4), 589-604.

Han G., C.G. Hannah, P.C. Smith, and J.W. Loder, 1997. Seasonal variation of the three-dimensional circulation over the Scotian Shelf, *J. Geophys. Res.*, 102(C1), 1011-1025.

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

Hendry, R. and I. He, 2004. Technical Report on Objective Analysis (OA) Project. In preparation for Can. Tech. Rep. Hydrog. Ocean Sci.

Wang, Y.M., 2001. GSFC00 mean sea surface, gravity anomaly, and vertical gravity gradient from satellite altimeter data. *J. Geophys. Res.*, 106(C12), 31,167-31,174.

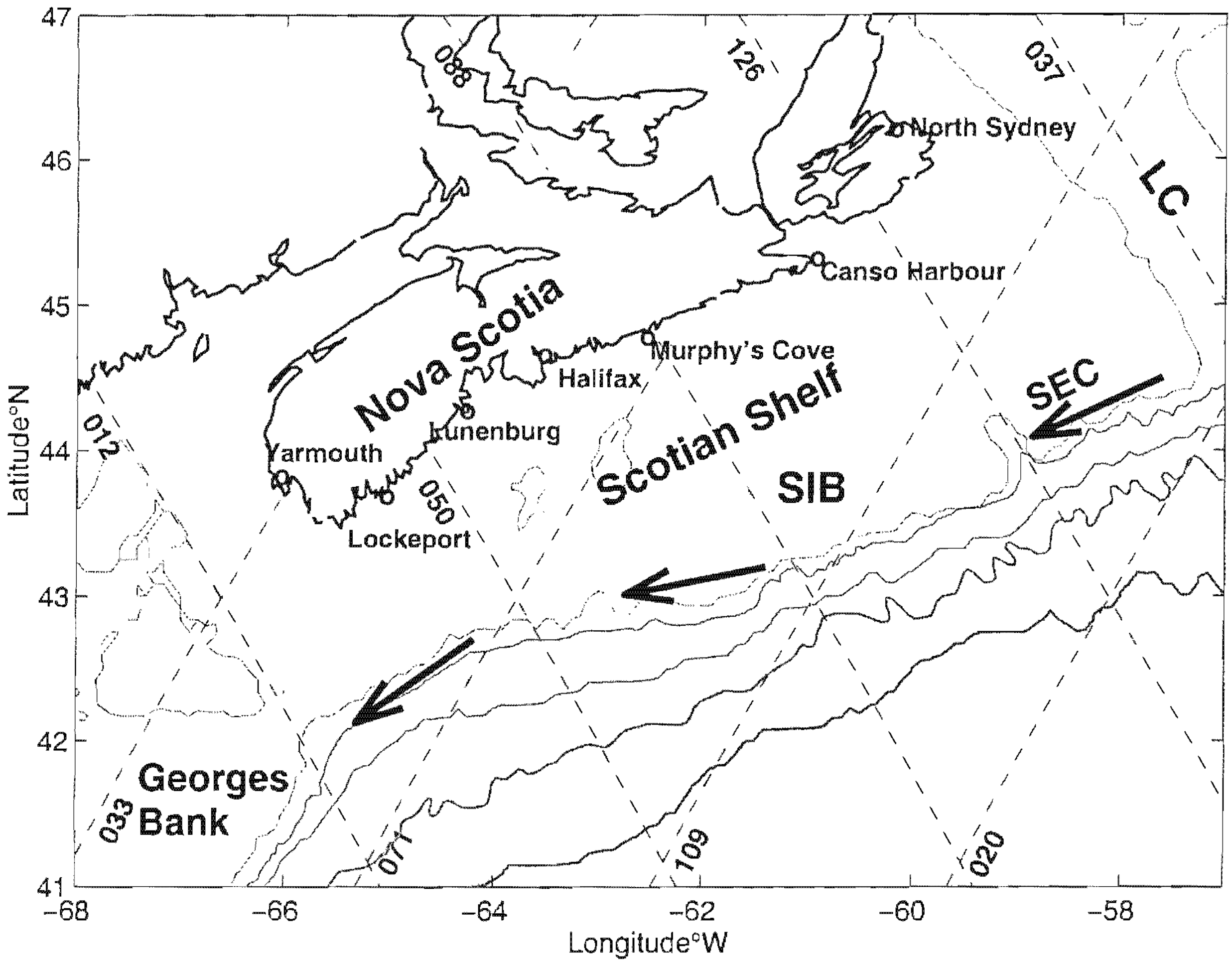


Figure 1. Map showing the Scotian Shelf and adjacent waters. The numerical labeled lines (thin dashed) are the selected T/P ground tracks on which the analysis is performed. The 200-, 1000-, 2000-, 3000- and 4000-m isobaths (grey lines) are also shown. SEC: Shelf-edge current. SIB: Sable Island Bank.

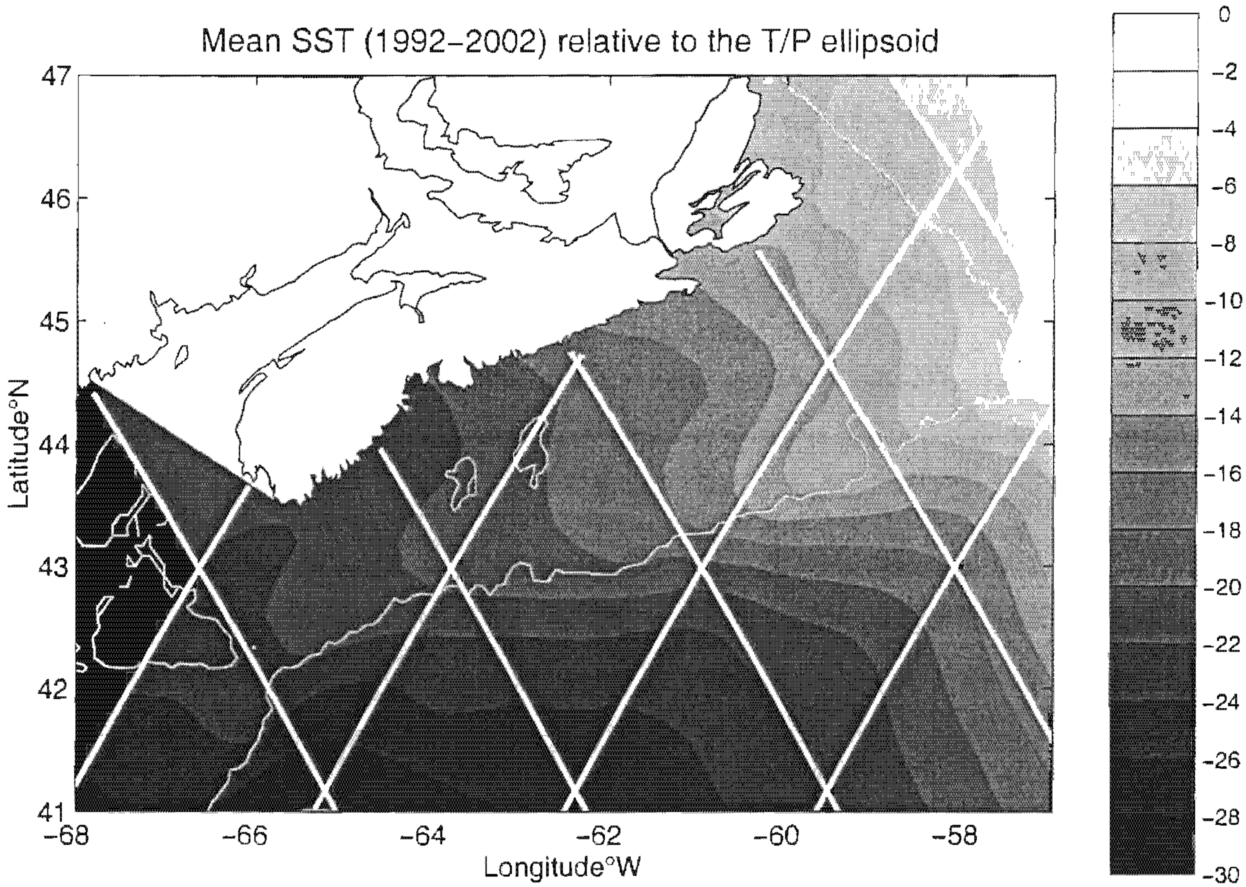


Figure 2. Mean sea surface height (m) relative to the T/P ellipsoid from the T/P data for the period from August 1992 to June 2002. The 200-m isobath (thin white lines) and T/P tracks (thick white lines) are also displayed.

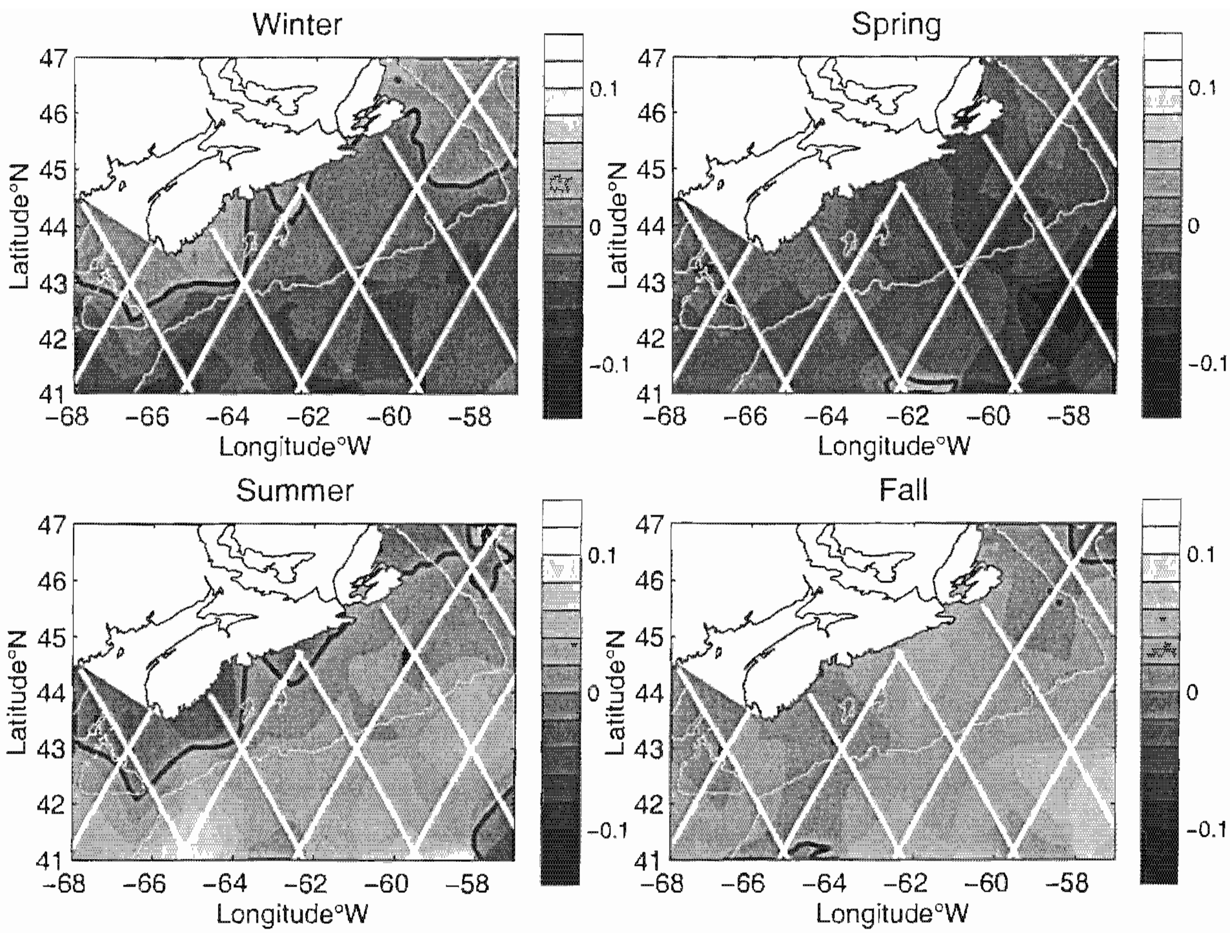
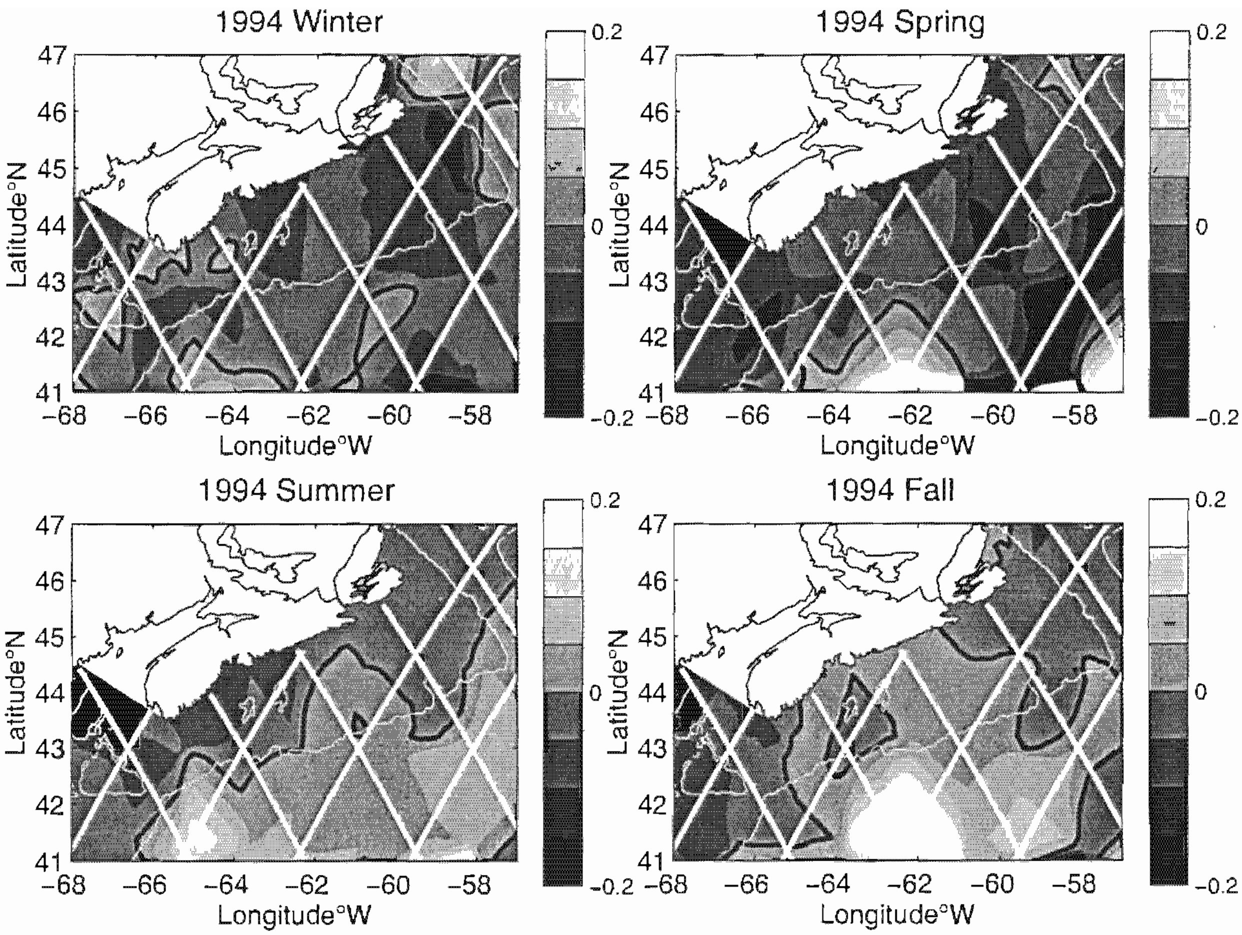
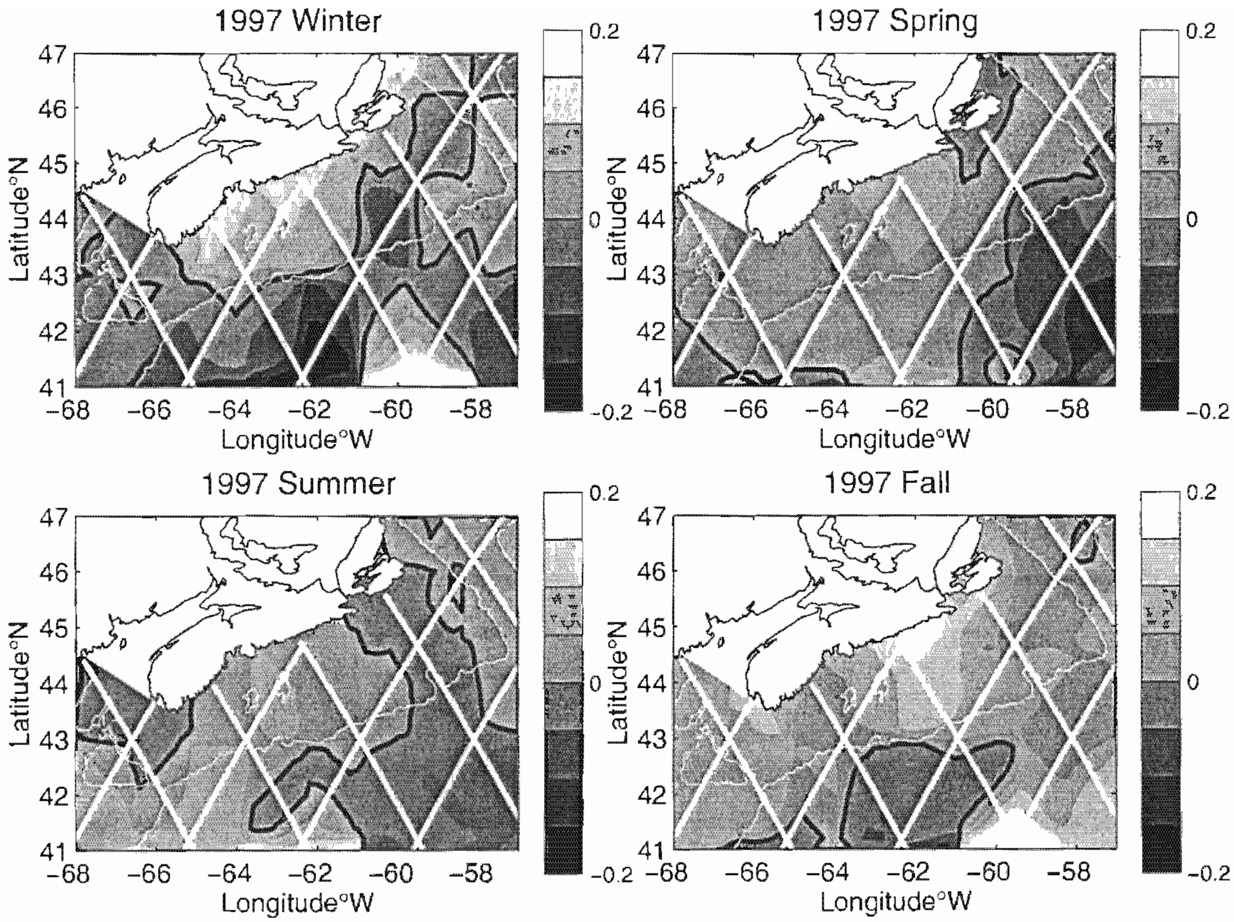


Figure 3. Long-term seasonal-mean sea surface height (m) from T/P data. The thick black lines depict zero contours. The 200-m isobath (thin white lines) and T/P tracks (thick white lines) are also displayed.



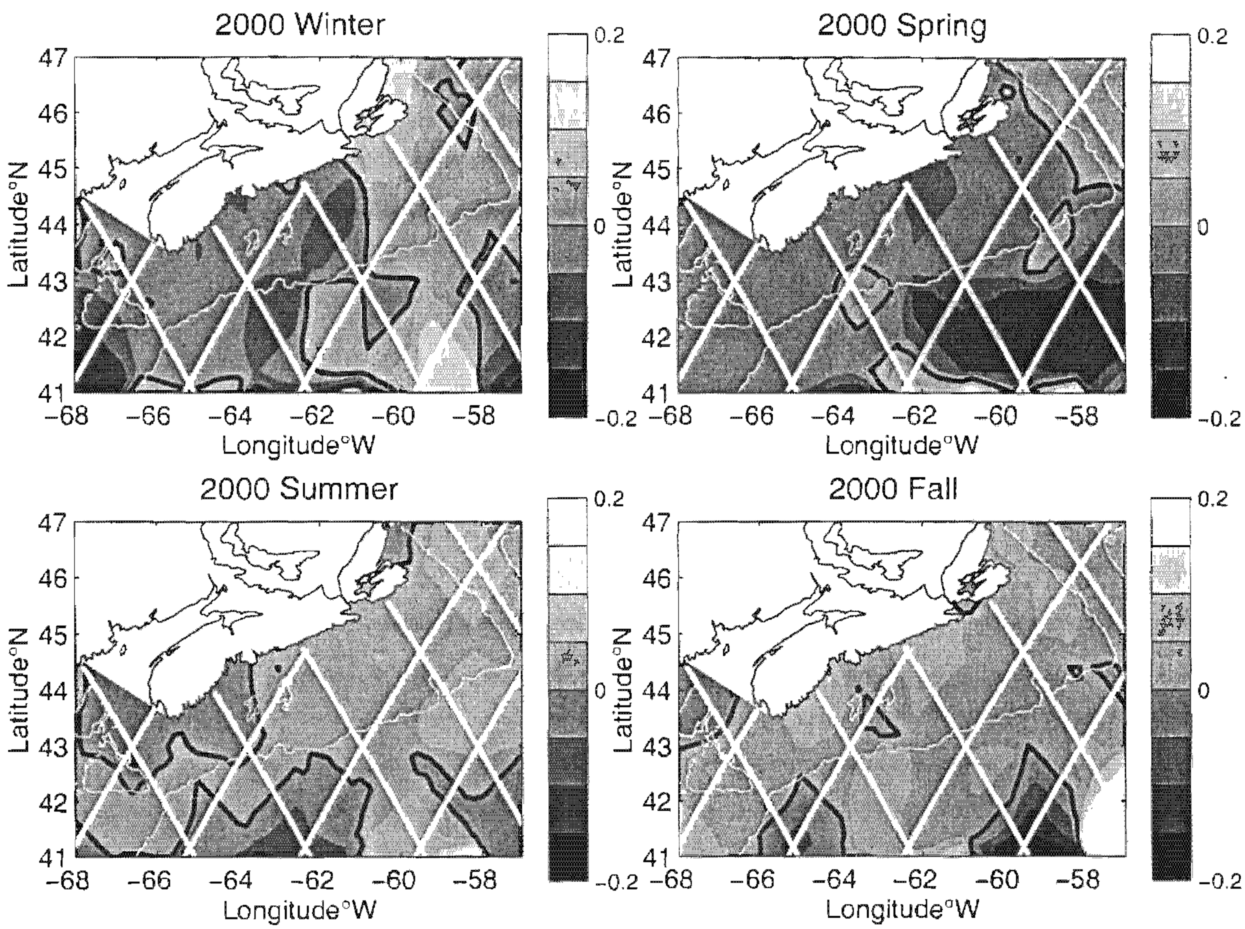
(a)

Figure 4. Seasonal-mean sea surface height anomalies (m) for (a) 1994, (b) 1997, and (c) 2000. The thick black lines depict zero contours. The 200-m isobath (thin white lines) and T/P tracks (thick white lines) are also displayed.



(b)

Figure 4. (continued).



(c)

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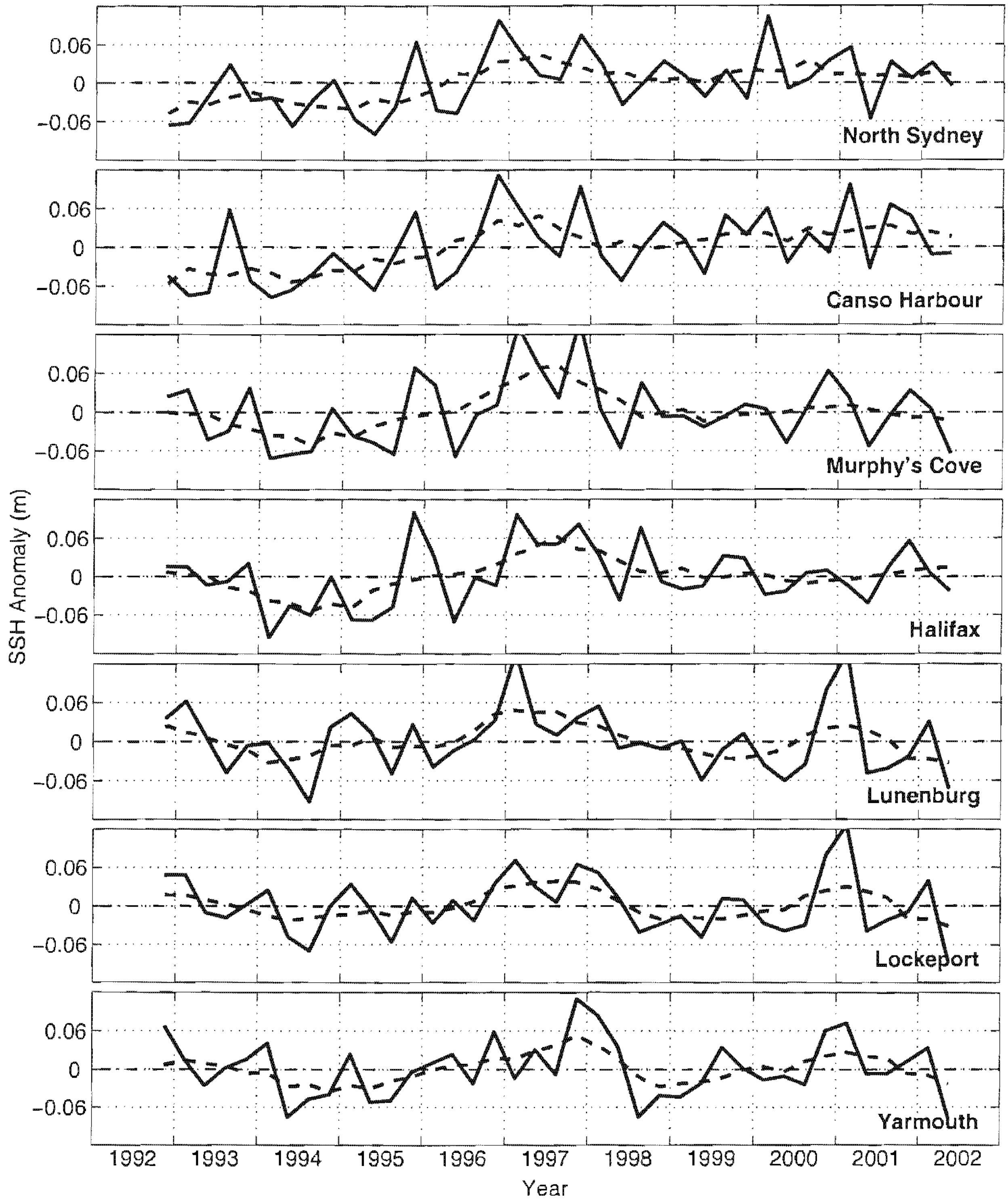


Figure 5. Seasonal-mean sea level anomalies (solid lines) at sites along the Nova Scotia coast estimated from T/P data. The dashed lines are the results with the annual and semi-annual cycles removed and subsequently smoothed with a five-point moving filter.

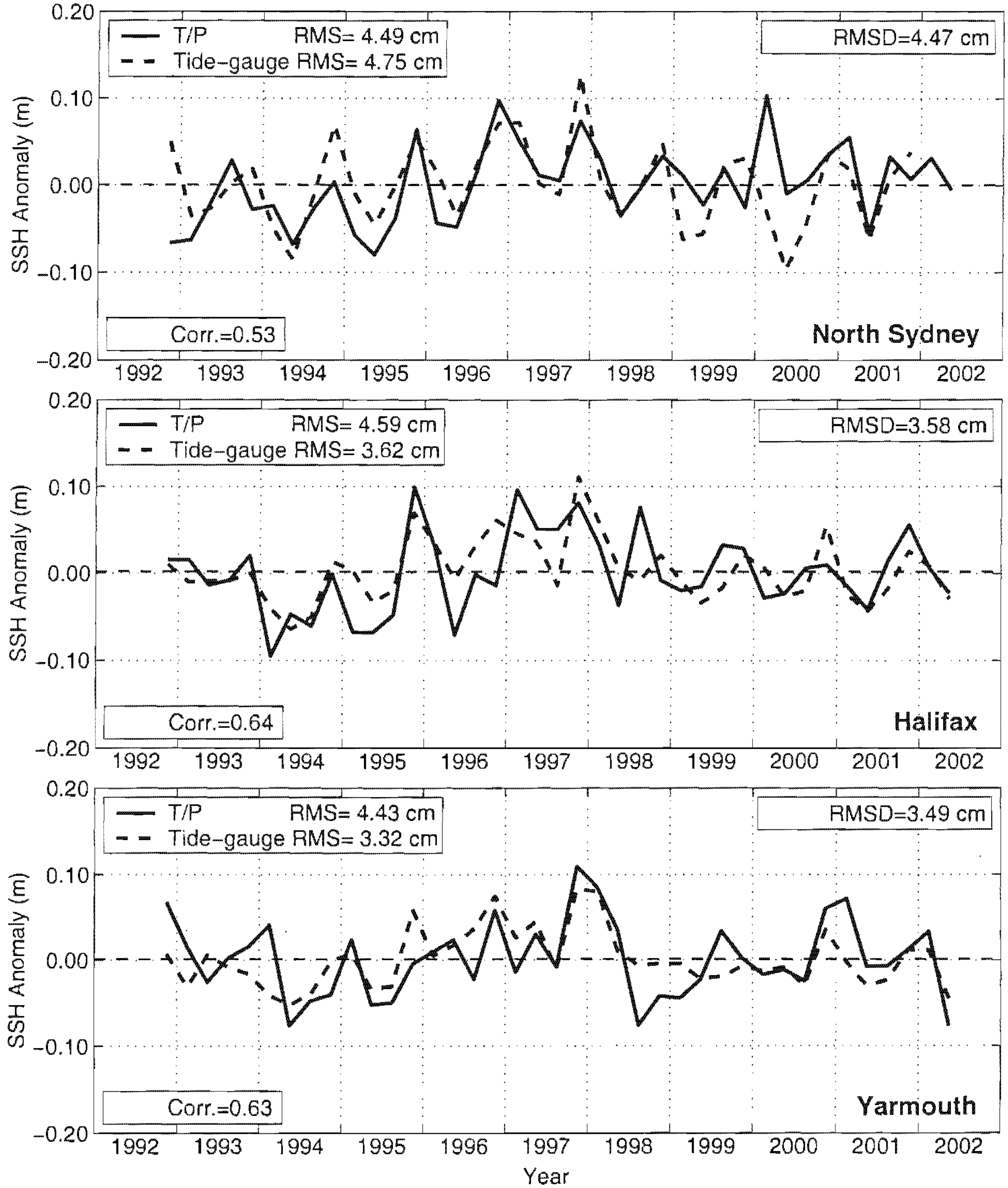


Figure 6. Comparison of T/P estimates and tide-gauge observations of seasonal-mean sea surface height anomalies. RMSD: RMS difference.

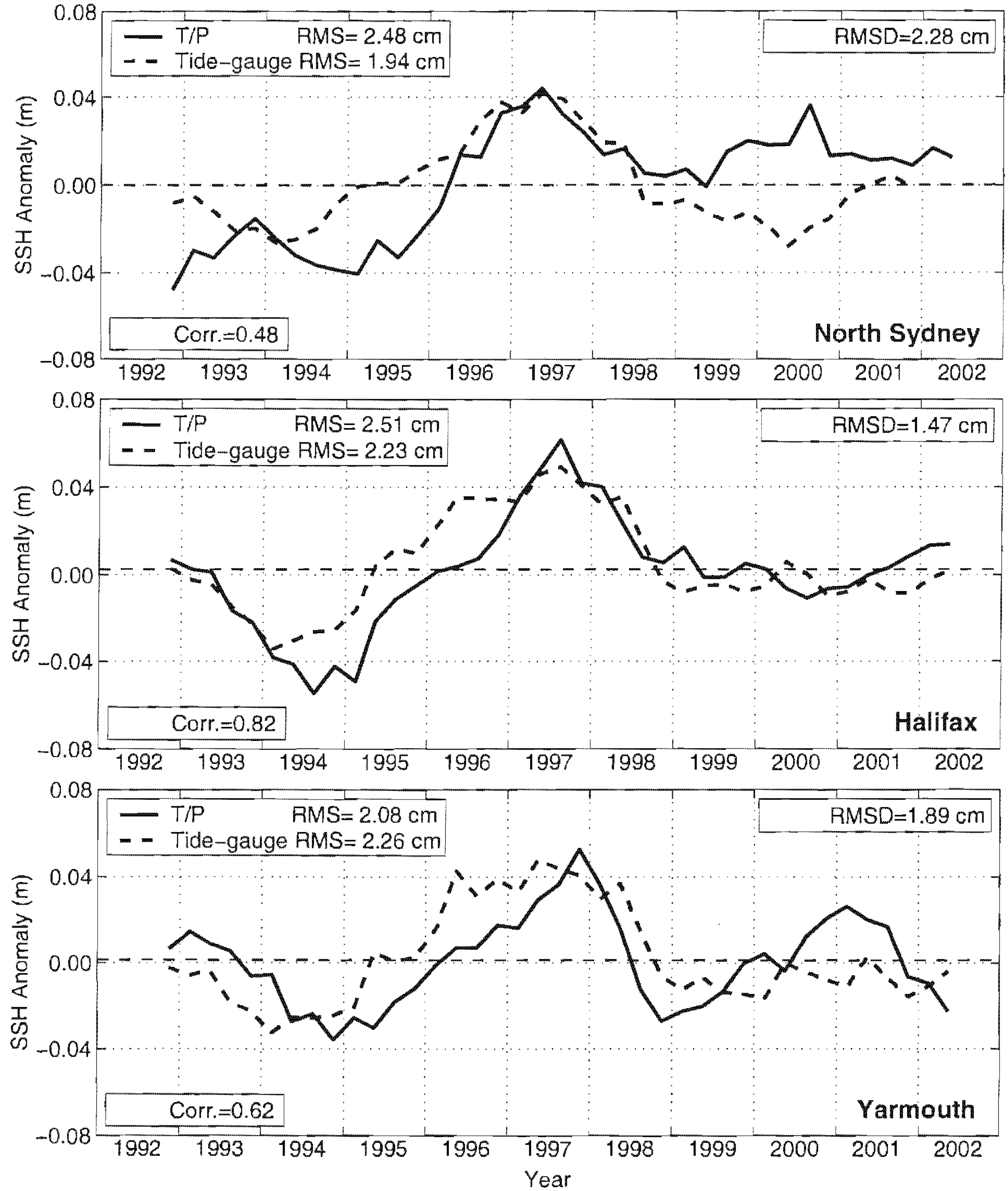
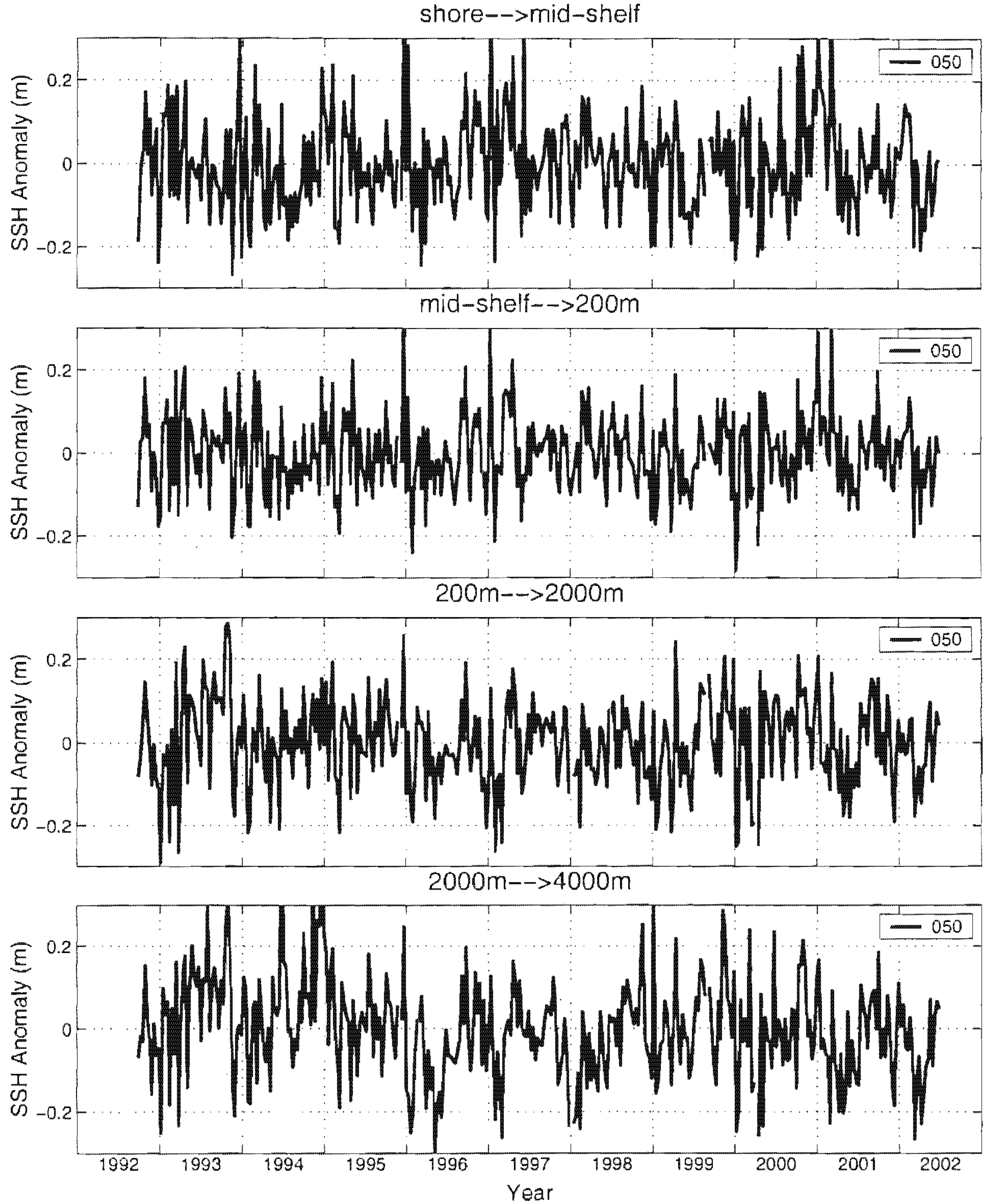
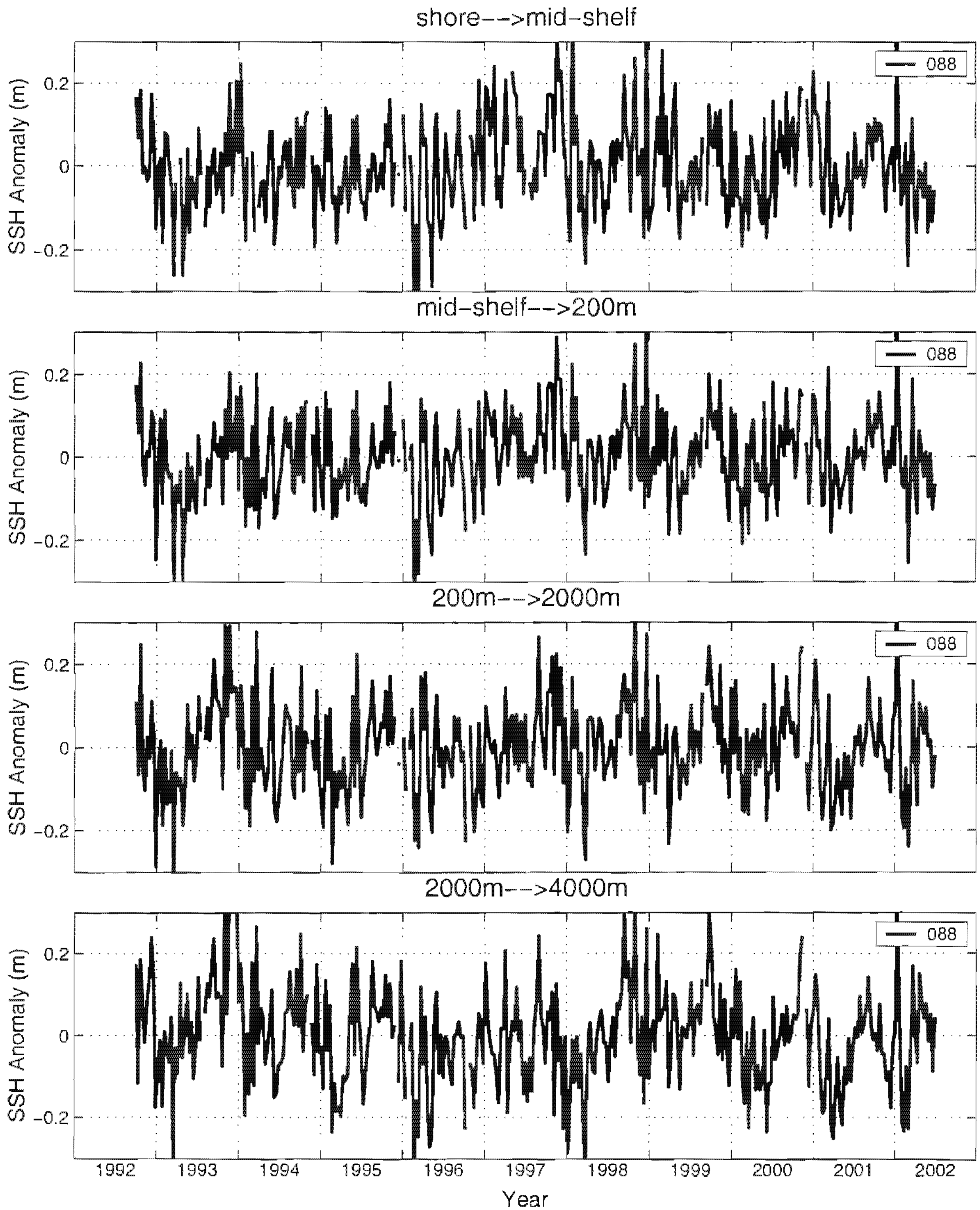


Figure 7. Same as Fig. 7, except for annual and semi-annual cycles being removed and subsequently being smoothed with a five-point moving filter.



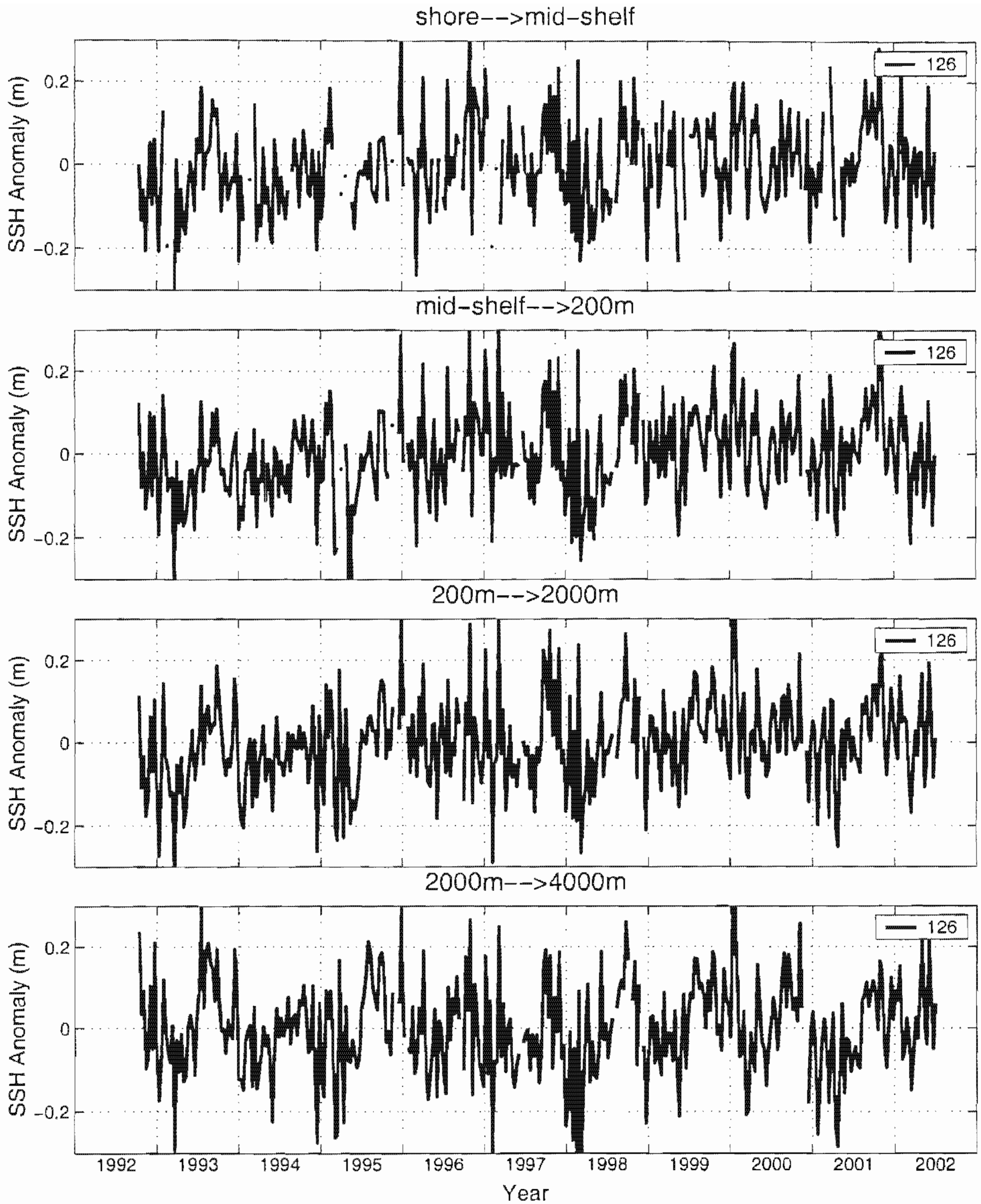
(a)

Figure 8. T/P SSH anomalies on Tracks (a) 050, (b) 088 and (c) 126 for the period from August 1992 to June 2002.



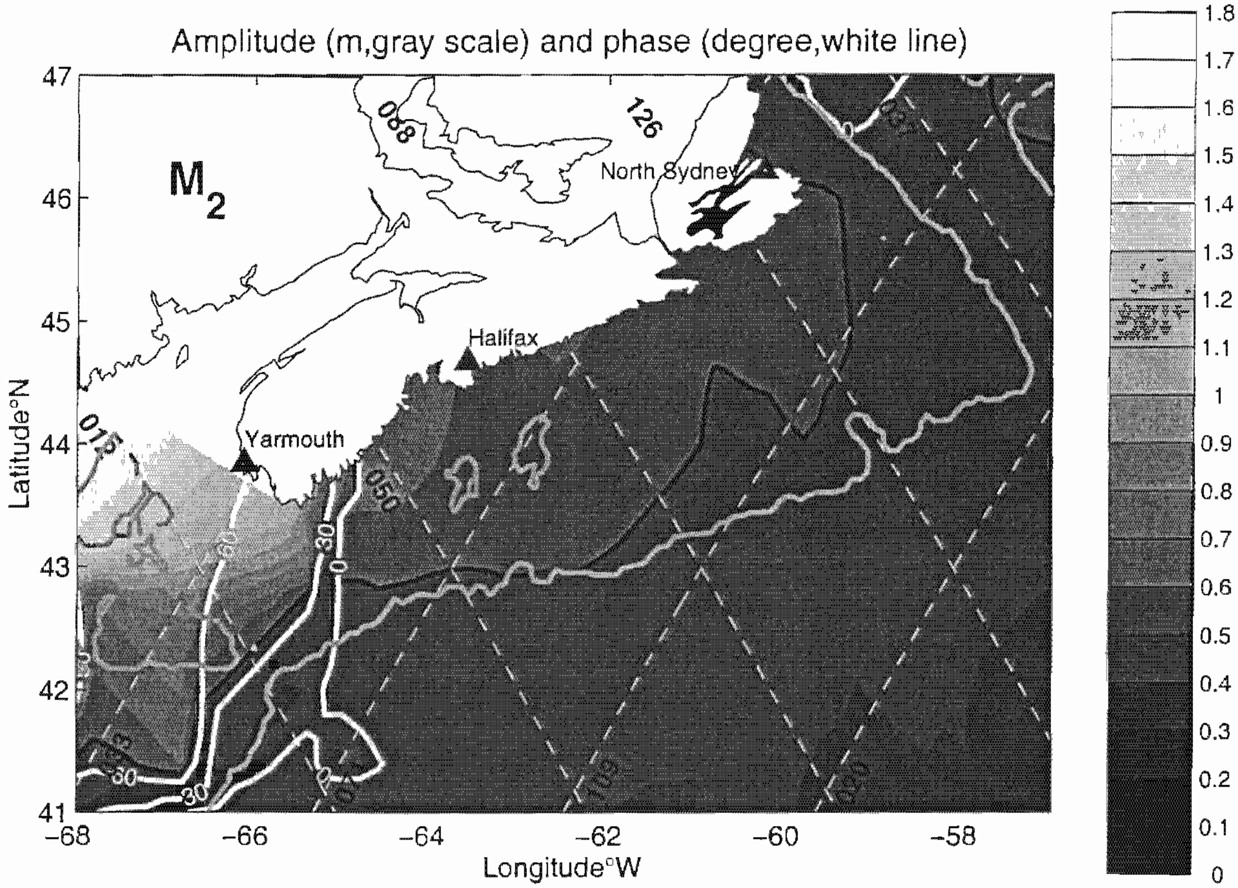
(b)

Figure 8. (continued).



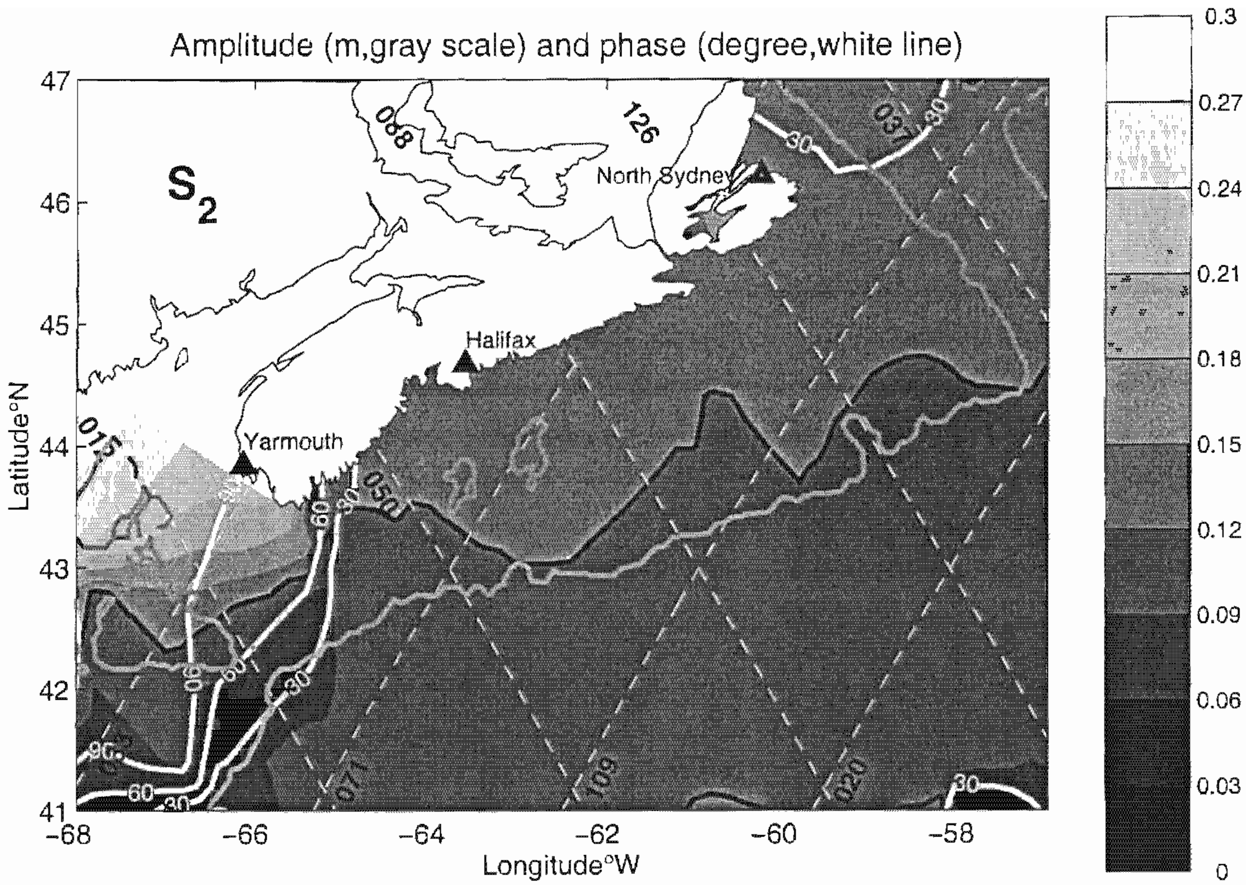
(c)

Figure 8. (continued).



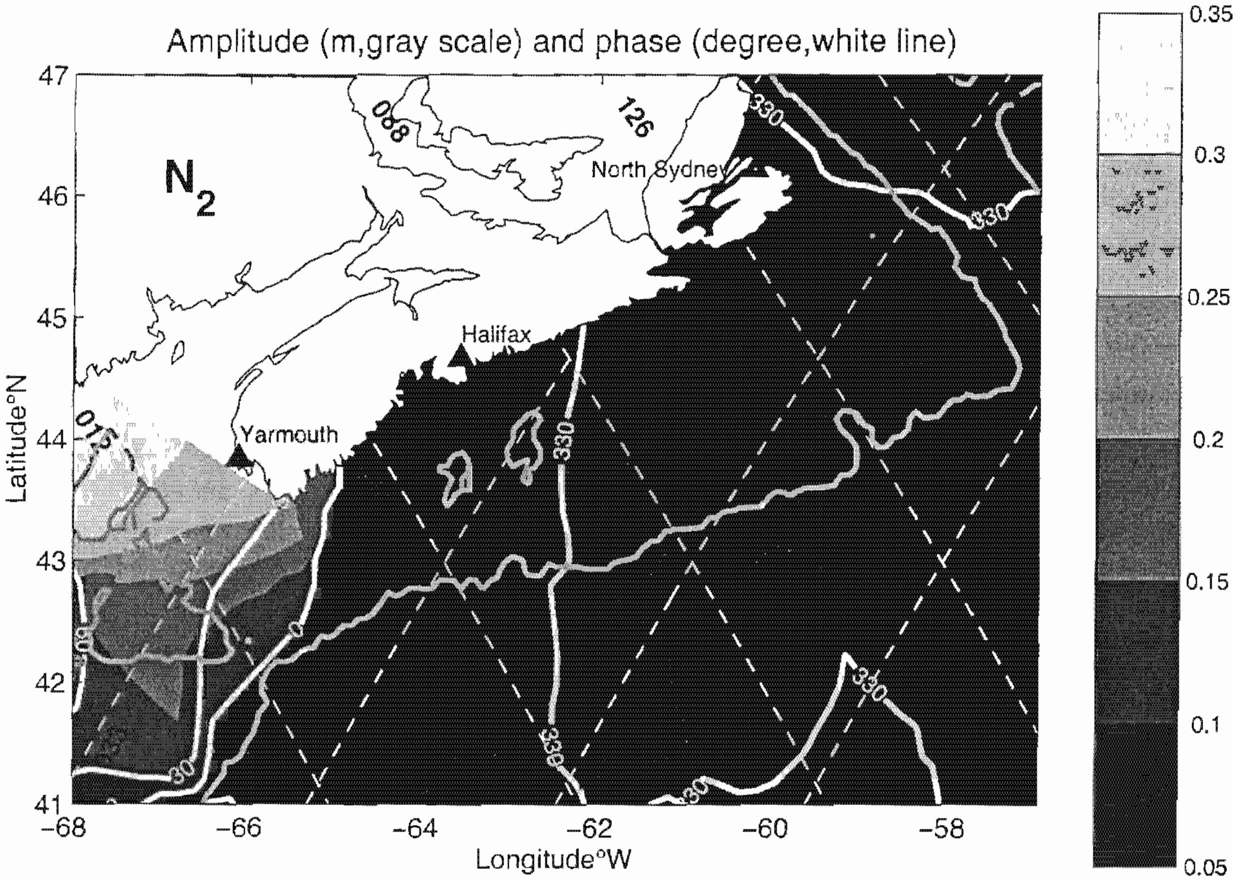
(a)

Figure 9. Co-amplitude and co-phase charts from altimetry for (a) M2, (b) S2, (c) N2, (d) K1, and (e) O1. The thick black line corresponds to 0.5, 0.12, 0.1, 0.08, and 0.04 m for M2, S2, N2, K1, and O1, respectively.



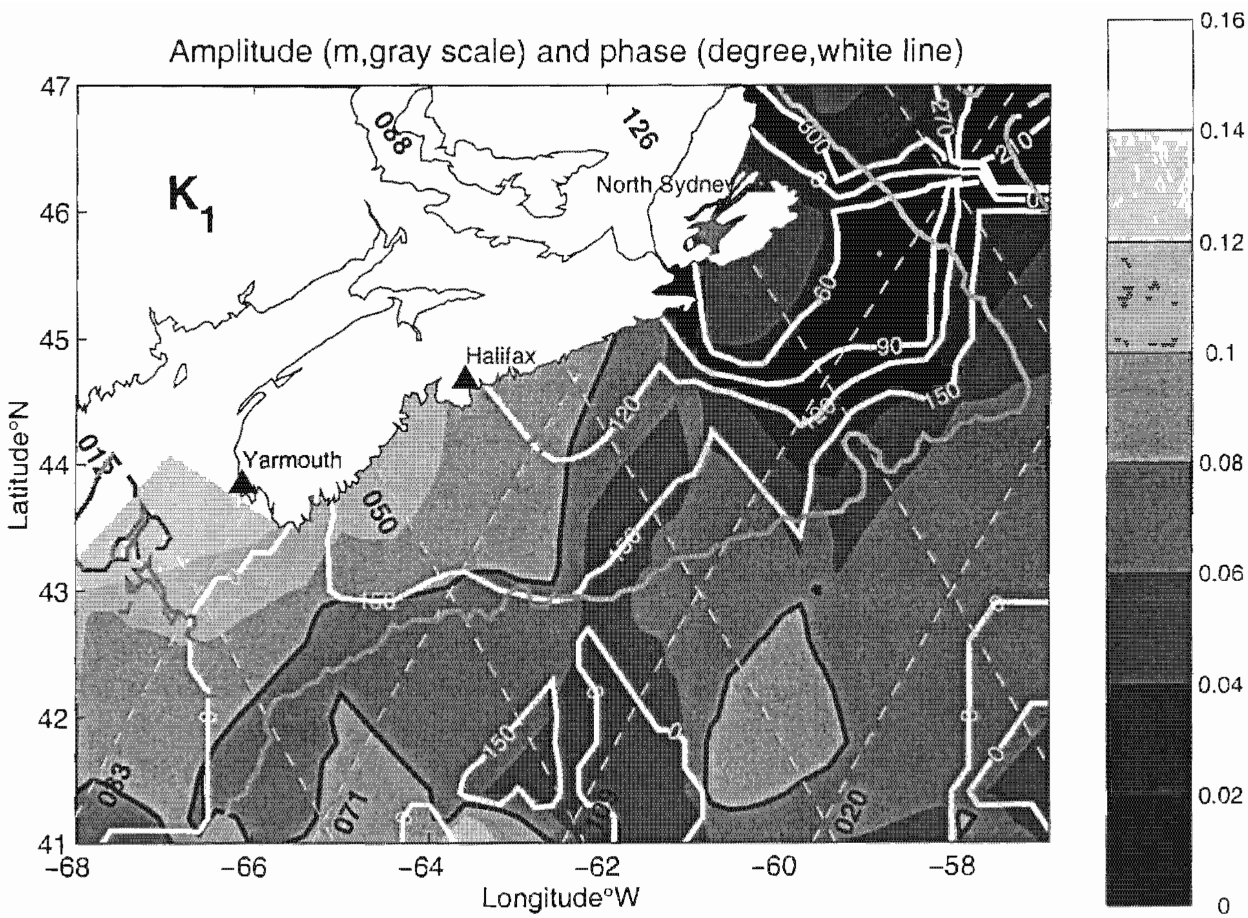
(b)

Figure 9. (continued).



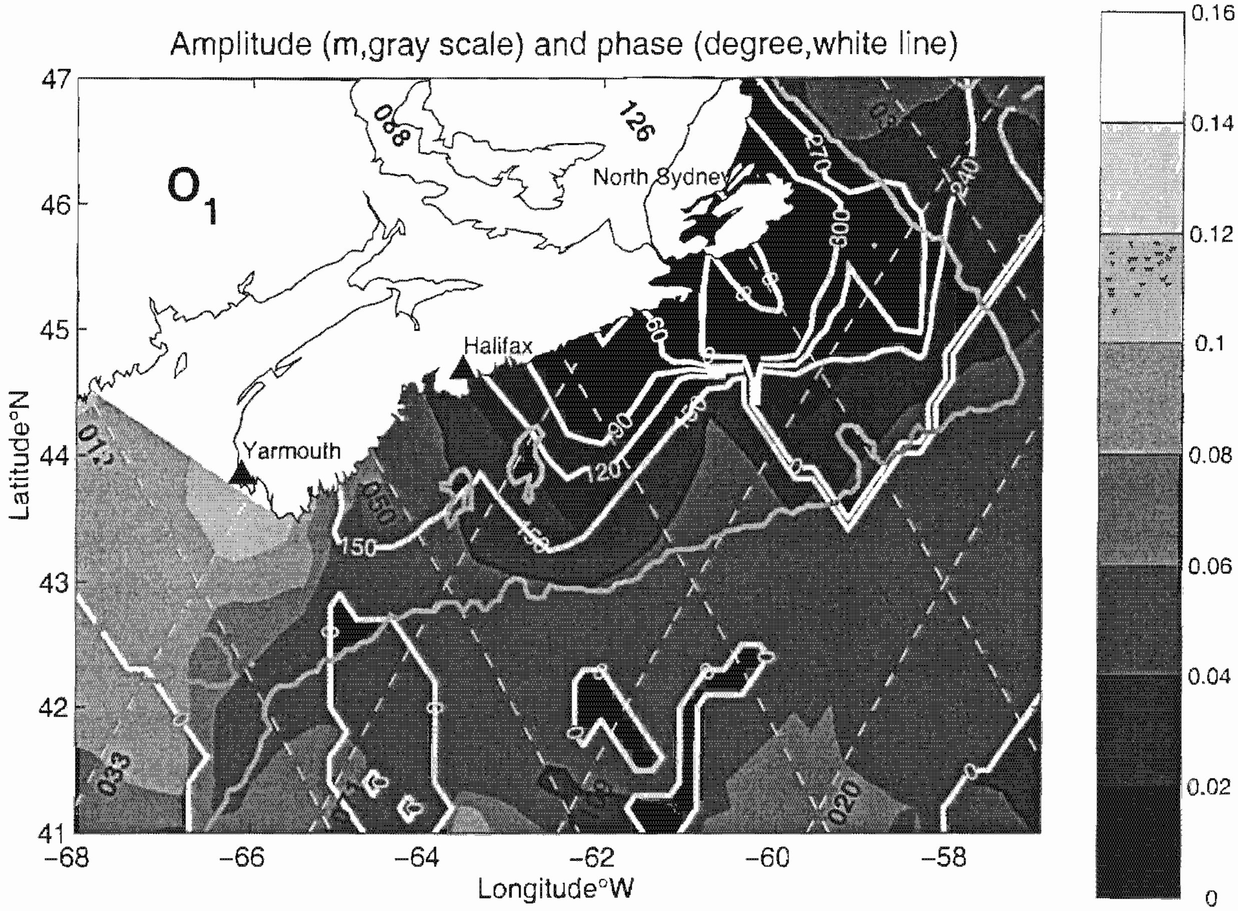
(c)

Figure 9. (continued).



(d)

Figure 9. (continued).



(e)

Figure 9. (continued).

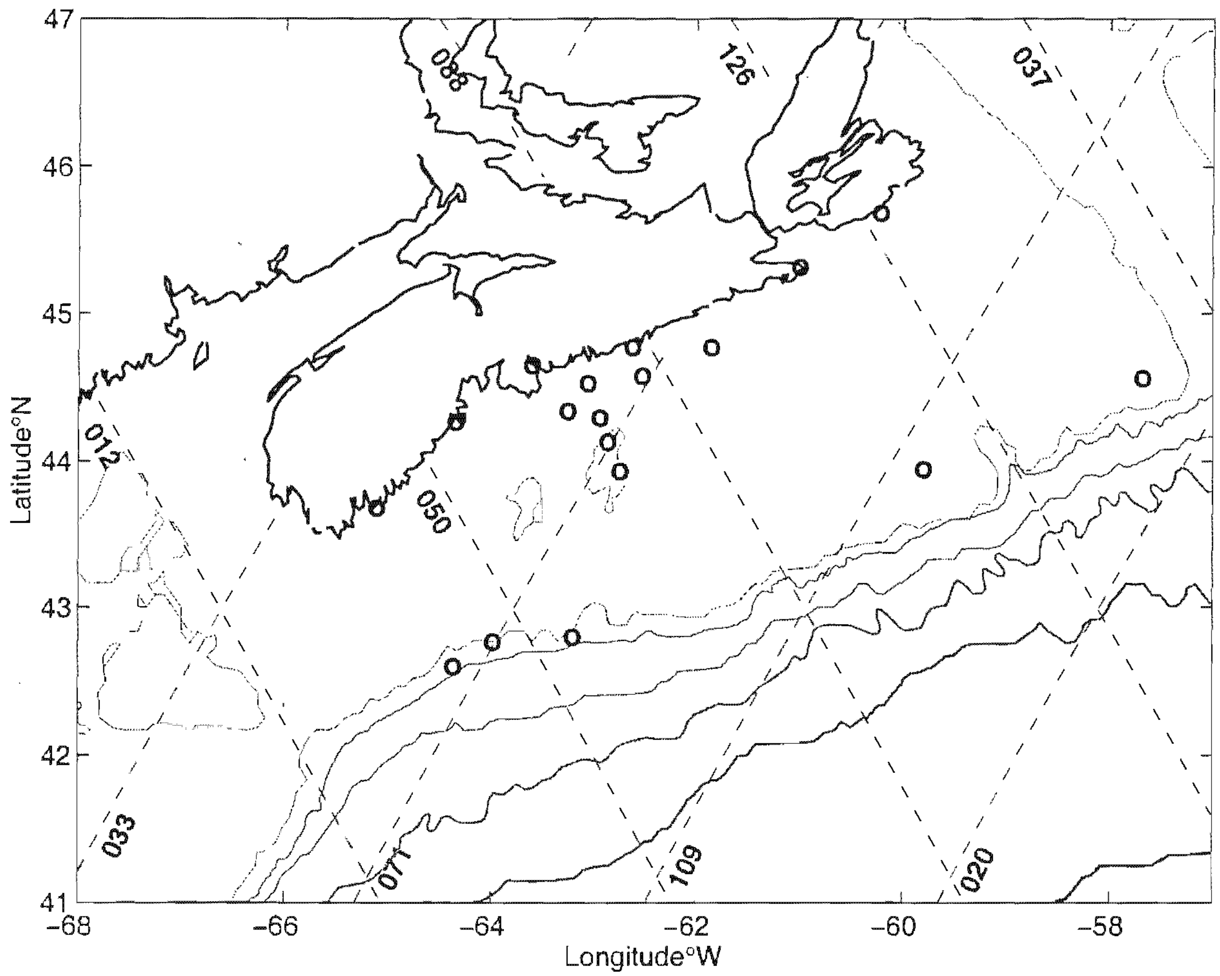
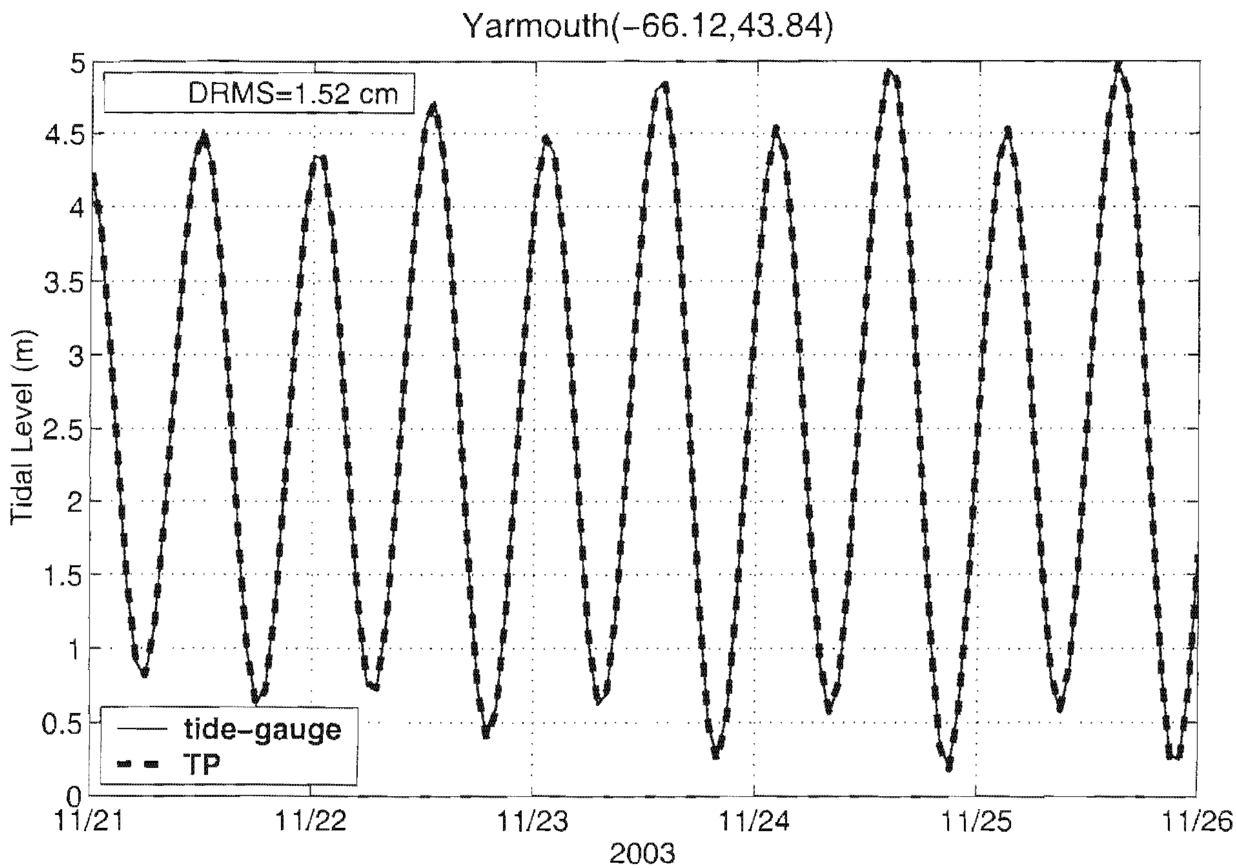
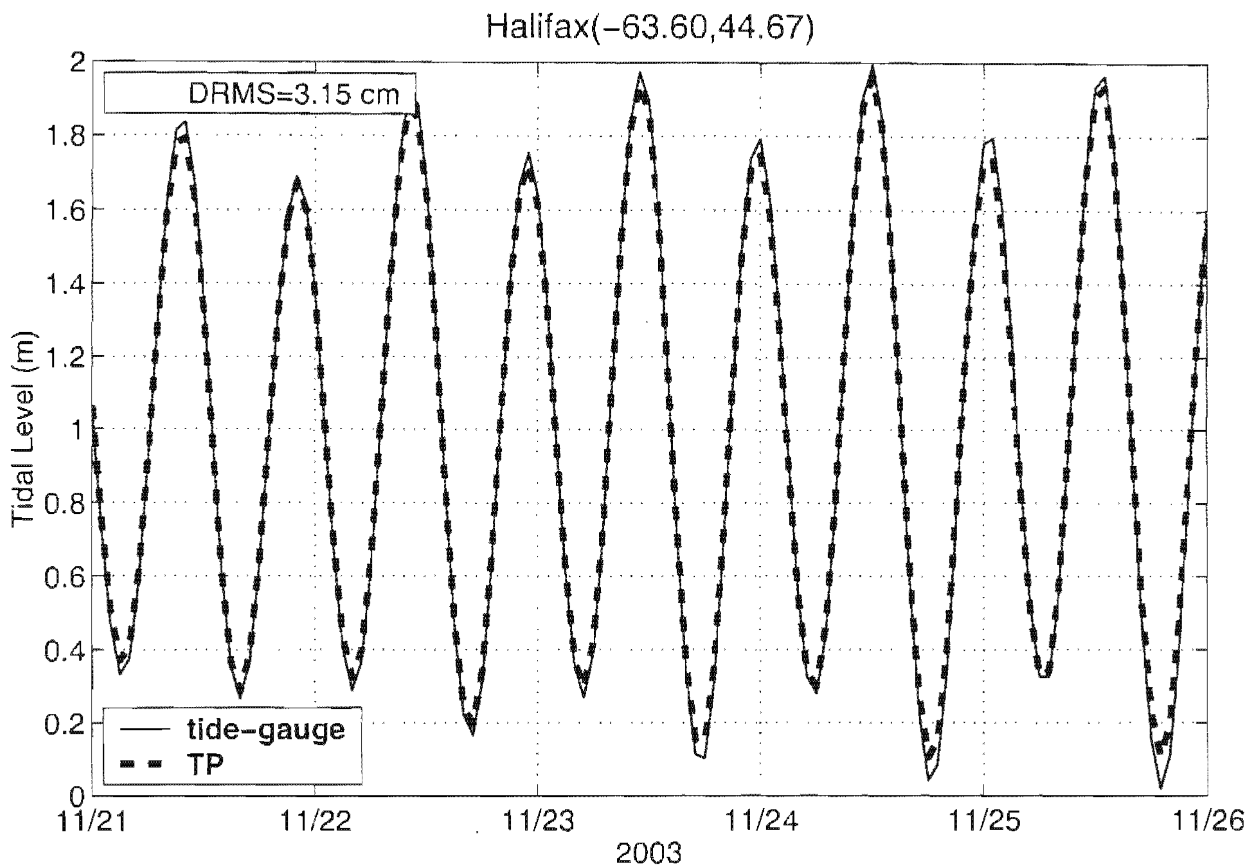


Figure 10. Locations of coastal tide gauges and pelagic bottom pressure gauges where T/P estimates are compared with tide-gauge observations (Table 4).



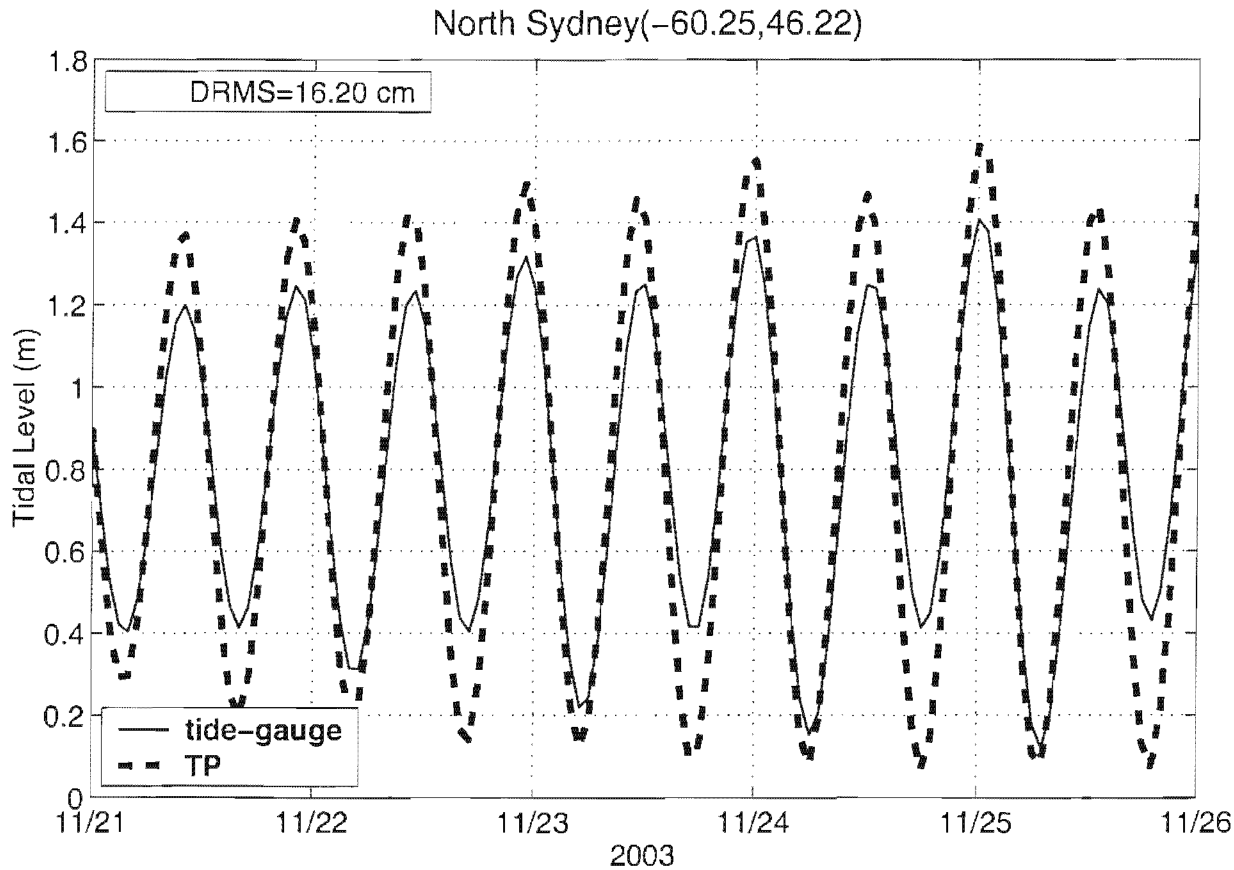
(a)

Figure 11. Predicted tidal sea level at (a) Yarmouth, (b) Halifax, and (c) North Sydney using T/P and tide-gauge derived parameters for the eight constituents.



(b)

Figure 11. (continued).



(c)

Figure 11. (continued).