RESEARCH ARTICLE

Annual sea level variations off Atlantic Canada from satellite altimetry

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Abstract: Annual cycle of sea level off Atlantic Canada has been investigated based on a merged satellite altimetry dataset and a monthly temperature and salinity dataset. The altimetric results were compared with coastal tide-gauge data and steric height calculated from the temperature and salinity dataset. There was a general north-south variation in the amplitude of the altimetric annual cycle, increasing from 4 cm in the Labrador Sea to 15 cm in the Gulf Stream and the North Atlantic Current Region. The annual cycle in the deep ocean can approximately be accounted for by the steric height variability relative to 700 m, in which the thermosteric effect was the dominant contributor. The halosteric effect over the continental slope, especially over the northern Labrador Slope was also important. While the thermosteric effect occurred dominantly at the top 100 m water column, there was substantial halosteric variation in the 100–300 m water column. The annual sea level cycle along the Canadian Atlantic coast showed a complicated pattern in amplitude, but the phase was highly coherent with the highest sea level in fall. The steric height accounts for a substantial portion of the coastal annual cycle, but other factors such as wind forcing may be equally important.

Keywords: sea level, annual cycle, thermosteric height, halosteric height, satellite altimetry, Northwest Atlantic

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1. Introduction

Sea level variation is due to an integrated manifestation of the ocean's interior variability in response to the force of oceanic, atmospheric, cryospheric and terrestrial origins. Traditionally, sea level has been monitored by coastal tide gauges. The distribution of present tide-gauge stations remains too sparse geographically to adequately represent spatial change of sea level. In the past two decades, satellite altimetry with nearly global coverage has complemented tide gauges in monitoring and understanding sea level variation on both global and regional scales (Fu and Cazenave, 2001; Vignudelli, Kostianoy, Cipollini *et al.*, 2011).

Satellite altimetry has been used to study coastal, shelf and slope sea level variability in the Northwest Atlantic. Han *et al.* (2002) studied annual sea level variation over the Scotian Shelf and Newfoundland Shelf using TOPEX/Poseidon along-track data from 1992–1998. They found that the annual cycle over the outer Scotian Shelf and the Scotian Slope could mostly be accounted for by steric height, while the coastal sea level off Eastern Newfoundland could be attributed to both local steric height from Petrie *et al.* (1983) and a large-scale wind forcing (Greatbatch, deYoung, Goulding *et al.*, 1990). Han (2004) derived the annual sea level cycle in the Gulf of St. Lawrence using TOPEX/Poseidon along-track data from 1992–1999 and showed approximate agreement between the altimetric results and tide-gauge data. On the inter-annual scale, altimetric sea level variability over the Scotian Shelf (Han, 2002), in the Gulf of St. Lawrence (Han, 2004), and over the Scotian Slope (Han, 2007) was found to be related to the Labrador Current strength, the Gulf Stream north-south movement, and the North Atlantic Oscillation. However, there are unanswered questions on the annual sea level cycle. For example, is there any systematic difference between the coastal and shelf ocean and the deep ocean? Is there any fundamental difference in the forcing mechanism?

This study aimed to investigate the regional characteristics of annual sea level variations off Atlantic Canada using gridded multi-mission satellite altimetric measurements from 1993 to 2010, a temperature and salinity climatology from 1945 to 2010. Annual harmonics of sea level variations are extracted from altimetric sea surface heights using a harmonic analysis method. Analyses emphasized on regional differences of annual sea level variations in the northern Northwest Atlantic and explore underlying forcing mechanisms.

2. Methodology

2.1 Altimeter Data Processing and Analysis techniques

Source of weekly merged sea surface height anomalies was used from AVISO (Archiving, Validation and Interpretation of Satellites Oceanographic data, viewd 15 November, 2015). The AVISO dataset is an objectively mapped product of TOPEX/Poseidon/Jason-1/Jason-2 (T/P/J), ERS-1, ERS-2, Geosat-Follow-on and Envisat altimeter data, with a 1/3° Mercator projection grid (Ducet, Le Traon and Reverdin, 2000). Standard corrections were made to account for wet troposphere, dry troposphere, and ionosphere delays, inverted-barometer responses, sea state bias, and ocean, solid Earth and pole tides.

Monthly-mean sea surface height anomalies was generated from the original weekly data and apply a harmonic analysis to the monthly-mean data from 1993 to 2010 to retrieve the annual cycle. The altimetric sea level anomalies are expressed as

$$\zeta(\phi,\lambda,t) = C\cos\omega t + S\sin\omega t + r \qquad (1)$$

where ζ is the sea level anomalies; φ and λ are longitude and latitude; t is the time; C and S are cosine and sine coefficients of the annual cycle that is to be determined; ω is the annual angular frequency; and r is the residual sea level anomalies. A least squares technique is used to solve Equation (1). The amplitude and phase was calculated from C and S.

2.2 Tide-gauge Data

Tide-gauge data along the Canadian Atlantic coast (Figure 1, Table 1) are collected by the Canadian Hydrograhic Service. Monthly-mean sea level data was obtained from the Permanent Service for the

Mean Sea Level (PSMSL, viewd 15 November, 2015). Data from 1993 to 2010 was used for all except for Nain where the period is from 2002–2010. The tide-gauge data were adjusted for the inverse barometer effect using the atmospheric pressure data from the North American Regional Reanalysis (NARR, viewed 15 November, 2015). A harmonic analysis similar to that described in Section 2.1 was carried out to retrieve the annual cycle from the adjusted tide-gauge data.

2.3. Ocean Temperature and Salinity Dataset and Steric Height

An updated version of monthly-mean temperature and salinity datasets (Ishii, Kimoto, Sakamoto, *et al*., 2006), based on their revised bias corrections of MBT/XBT data (Ishii and Kimoto, 2009), was used to calculate the steric height. The temperature and salinity fields were objectively analyzed on a 1° by 1° grid at the upper 16 standard levels (the deepest level is 700 m) for 1945-2010. Various historical hydrographic datasets were used in the objective analysis, including the latest version of the observational data, climatology and standard deviations compiled by the National Oceanic and Atmospheric Administration/ National Oceanographic Data Center (NODC). Tropical and subtropical Pacific Ocean sea surface salinity dataset for 1970–2001 and a global database archived by the Global Temperature-Salinity Profile Program of NODC from 1990 to 2010 was used for this studies, and made the drop rate correction for the XBT data.

In this study, the steric height relative to 700 m (or the deepest level with valid temperature and salinity data) was computed based on the above temperature and salinity dataset. The formula to compute steric height can be expressed as:

$$h_{steric} = \frac{1}{9.8}\int_0^{P_2}\left(\frac{1}{\rho(S,T,p)} - \frac{1}{\rho(35,0,p)}\right)dp \qquad (2)$$

Where h_{steric} is the steric height; $S, T,$ and p are the monthly salinity, temperature, and pressure; P_2 is the pressure at 700 m or the deepest depth with valid temperature and salinity data; and ρ is the density computed according to the equation of state.

Steric height anomalies were generated by removing temporal means at each location. A harmonic analysis similar to the analysis described in Section 2.1 was carried out to retrieve the annual cycle from the steric height

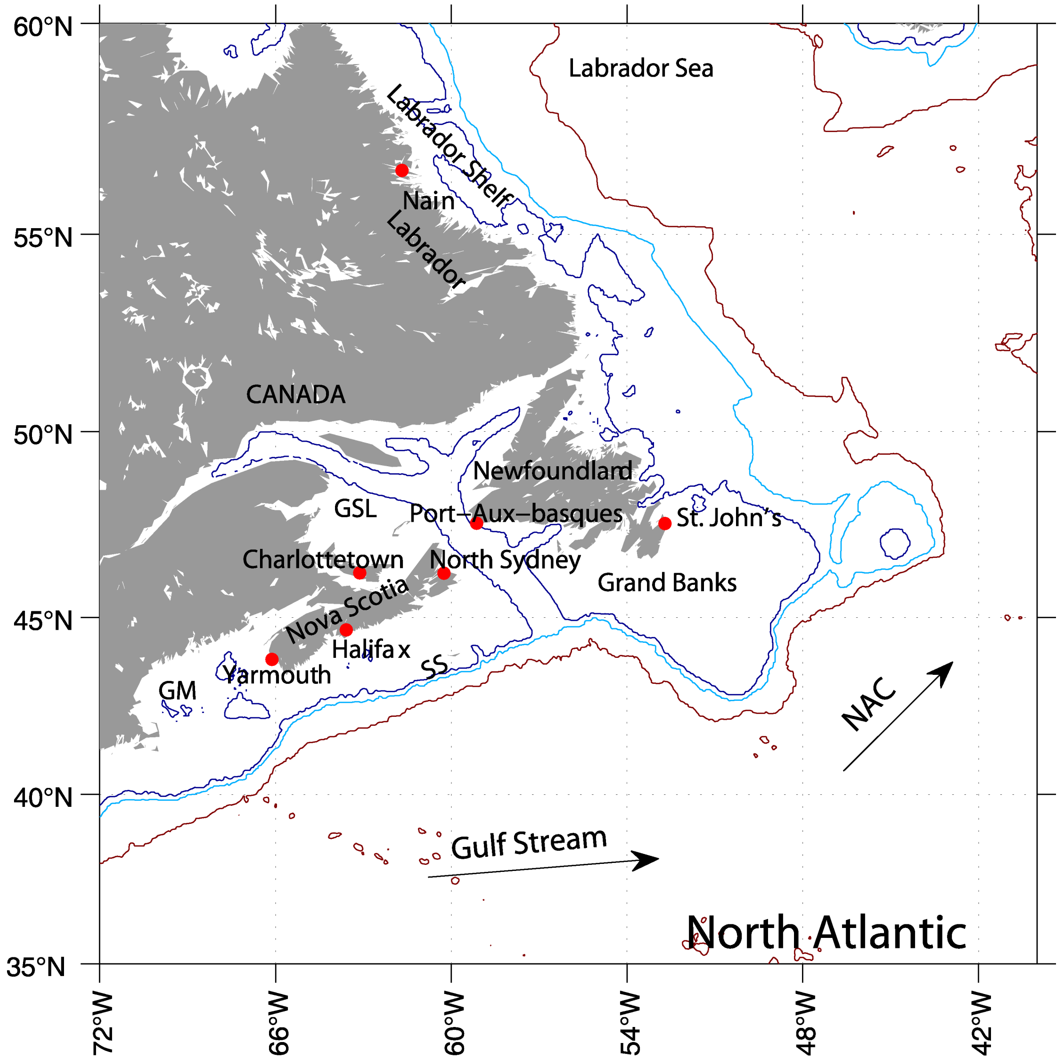

Figure 1. Map showing the Northwest Atlantic and its vicinity. Red dots were the locations of coastal tide-gauge stations. The 200-, 1000- and 3000-m isobaths were also shown. GM: Gulf of Maine; GSL: Gulf of St. Lawrence. NAC: North Atlantic Current; SS: Scotian Shelf.

Table 1. Locations of tide-gauge stations

Station	Longitude (°E)	Latitude (°N)
St. John's	–52.71	47.56
Port-Aux-basques	–59.13	47.57
North Sydney	–60.25	46.22
Halifax	–63.59	44.66
Yarmouth	–66.12	43.84
Charlottetown	–63.12	46.23
Nain	–61.68	56.55

anomalies for 1993–2010 (the altimetric data period) and for 1945–2010. The results for both periods were almost the same (Table 2), therefore presenting the annual cycle for 1993–2010 which is consistent with the altimetric and tide-gauge data period.

Thermosteric height and halosteric height were calculated to examine the relative contribution of temperature and salinity variations to steric height anomalies. The thermosteric height was estimated by using the monthly-mean temperature and the long-term (1993–2010) mean salinity S_0.

$$h_{thermosteric} = \frac{1}{9.8}\int_0^{P_2}\left(\frac{1}{\rho(S_0,T,p)} - \frac{1}{\rho(35,0,p)}\right)dp \quad (3)$$

Where $h_{thermosteric}$ is the thermosteric height. The halosteric height is estimated by subtracting the thermosteric height from the steric height.

3. Spatial Features of the Annual Cycle

The least squares analysis extracts the annual cycle of

Table 2. The amplitude and phase (year day) of the annual cycle from tide-gauge data, steric height, and altimetry data over 1993–2010.

Station	Tide Gauge		Steric Height		Altimetry	
	Amplitude (cm)	Phase (year day)	Amplitude (cm)	Phase (year day)	Amplitude (cm)	Phase (year day)
St. John's	7.2	327	3.4 (3.6)	273 (270)	5.4	330
Port-Aux-basques	2.2	285	5.1 (4.8)	263 (260)	2.1	308
North Sydney	6.2	314	6.0 (5.6)	262 (258)	5.3	310
Halifax	4.1	335	2.4 (3.3)	288 (264)	4.7	325
Yarmouth	2.2	326	0.7 (2.1)	219 (249)	4.2	334
Charlottetown	3.9	325	5.8 (5.1)	244 (250)	4.4	307
Nain	3.7	299	5.6 (4.9)	263 (275)	3.6	278
RMS difference	N/A	N/A	2.2 (1.8)	63 (59)	1.1	15
Mean difference	N/A	N/A	−0.1 (0.0)	−57 (−55)	−0.0	−3

The root mean square (RMS) and mean differences between the altimetric and tide-gauge data and between steric height and tide-gauge data were shown. The steric height values in parentheses were for the period over 1945–2010.

sea level from the altimetric data from 1993–2010. In this section, examination of amplitude and phase of the annual cycle of altimetric sea levels and compared the altimetric results with coastal tide-gauge measurements and steric heights was calculated from temperature and salinity obtained from Ishii *et al* (2006) and Ishii and Kimoto (2009).

3.1 Deep-ocean Variability

There was significant spatial variability in the amplitude of the altimetric annual cycle, from 4 cm in the Labrador Sea to 15 cm in the Gulf Stream and the North Atlantic Current region (Figure 2). The phase (the time of annual maximum sea level) pattern indicates that the annual sea level was higher in September/October in deep ocean.

Steric height relative to 700 m (Figure 3) for the deep ocean was calculated (water depth equal or greater than 700 m) based on monthly-mean temperature and salinity for 1993–2010 (Ishii et al. 2006; Ishii and Kimoto, 2009). On average the annual cycle of the setric height peaks in September/October, close to the altimetric results over the deep Northwest Atlantic. The steric height variability also weakens from the south to the north, with the magnitude of ~15 cm in the Gulf Stream region, 10 cm in the North Atlantic Current region and 4 cm in the Labrador Sea. An average altimetric result was calculated for the deep ocean (greater than 700 m) onto the 1° by 1° grid as for

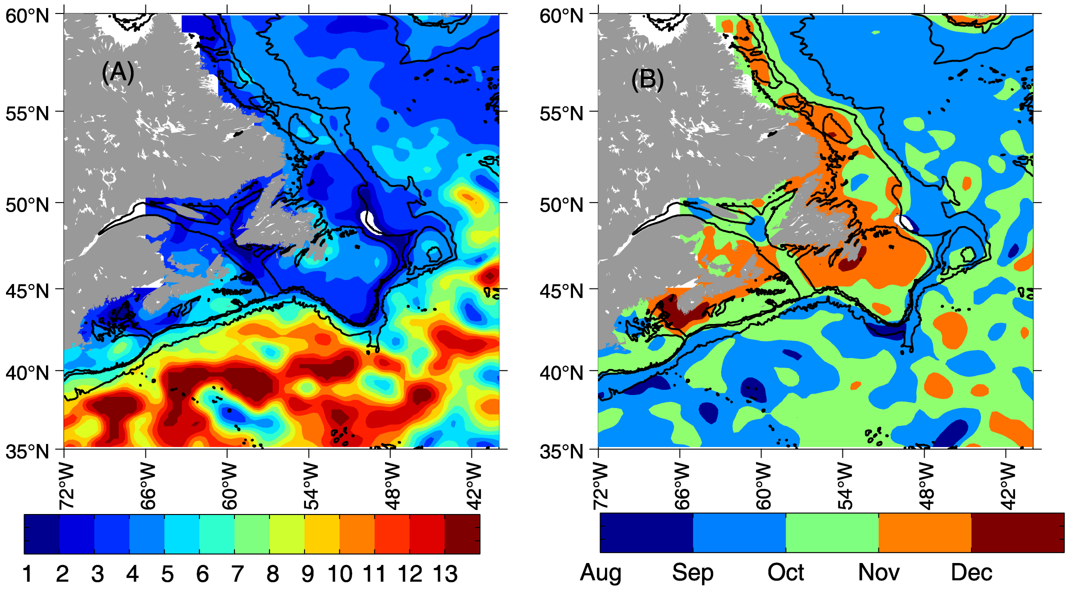

Figure 2. (A) Amplitude (cm) and (B) phase of annual sea level cycle from altimeter data in the Northwest Atlantic. The phase indicates the time (month) when the annual sea level is highest. The 200-, 1000- and 3000-m isobaths were shown.

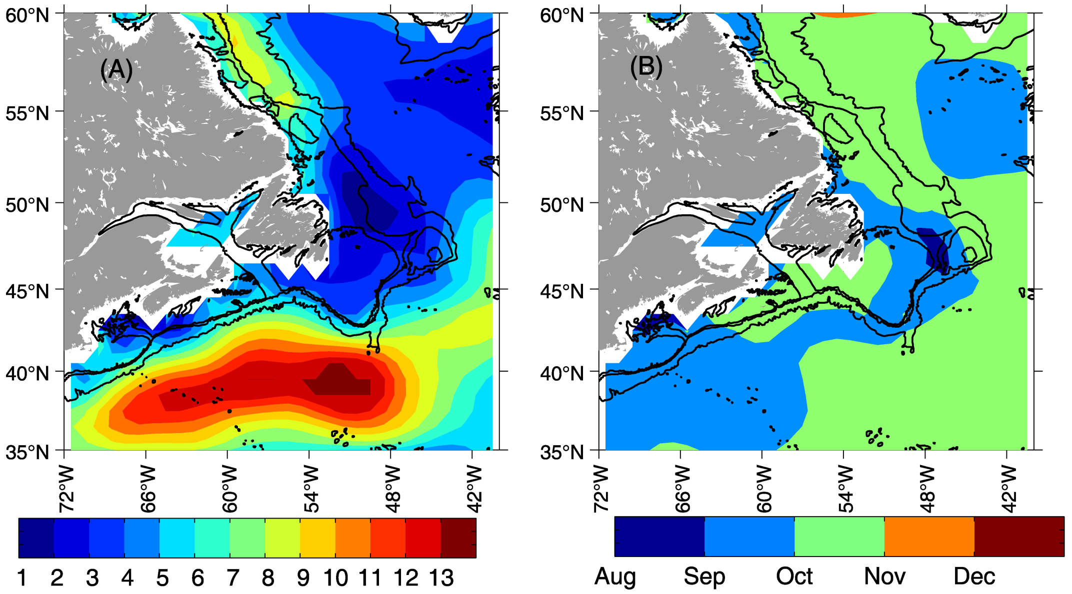

Figure 3. Same as Figure 2 but for steric height based on Ishii *et al.* (2006) and Ishii and Kimoto (2009) 1° by 1° temperature and salinity dataset.

the steric height. There was approximate agreement between the averaged altimeteric result and the steric annual cycle (Figure 4). The root mean square (RMS) differences in amplitude and phase were 2.1 cm and half a month, respectively. Offshore of the 3000-m isobaths the ratios of the steric height amplitude to the altimetric amplitude were averaged to be 0.98 and 0.84 south and north of 50°N, respectively. Therefore, the annual sea level change in the deep Northwest Atlantic can mainly be accounted for by the steric height

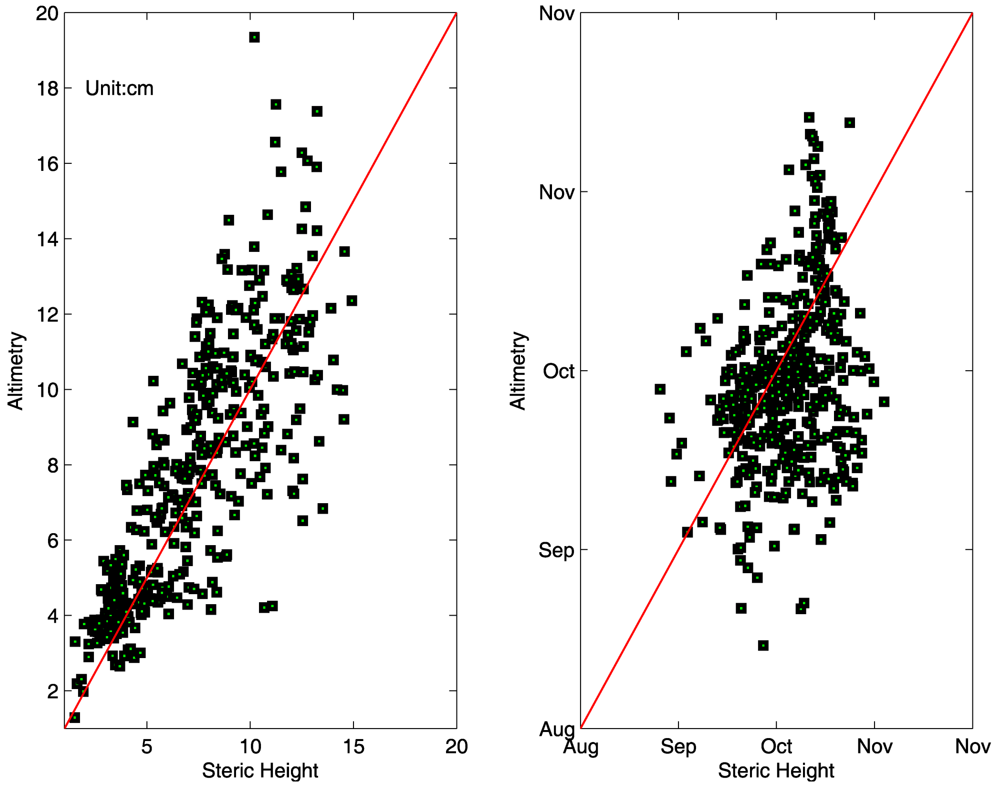

Figure 4. Scatter diagram comparing the amplitude and phase of the annual cycle from satellite altimetry and steric height in the deep ocean (greater than 700 m). The altimetric results were also averaged onto the 1° by 1° grid as for the steric height.

variability. In addition to the steric height, altimetric height has a component contributed by mass change. Annual cycle associated with the mass change (not shown) was derived from the 1° by 1° gridded Gravity Recovery and Climate Experiment (GRACE) data over 2003–2014 (Jet Propulsion Laboratory California Institute of Technology, viewed 15 November, 2015). However, it was observed that the addition of the mass change contribution with the steric height, does not improve agreement with the altimetric results for the annual cycle in our study region, which may be due to larger uncertainties associated with the GRACE data. Furthermore, there are notable differences in the spatial distribution between the altimetric result (Figure 2) and steric height (Figure 3) along the Gulf Stream and the North Atlantic Current, where the former showed significant spatial variability in the amplitude, mainly resulting from the aliasing of meandering and mesoscale eddy variability.

The decrease of the magnitude of the annual cycle from the south to the north represents the change in the forcing mechanisms. Generally, the annual cycle of steric height can be accounted for by that of the thermosteric height (Figure 5) which was associated with the annual temperature change. It was further discovered that the thermosteric effect occurred dominantly in the top 100-m water column, except along the Gulf Stream (Figure 6). The amplitude of the annual cycle for the temperature averaged over the top 100 m decreases significantly from the mid-latitude Northwest Atlantic to the subpolar Labrador Sea (Figure 7).

Over the northern Labrador Slope, the steric height variability was dominated by the halosteric effect associated with the salinity change (Figure 3 and Figure 8). In some other places over the continental slope such as off the southeastern Grand Banks and off southwestern Scotian Shelf, the annual cycle of halosteric height (Figure 8) was also significant. The annual cycle of the halosteric height was nearly out of phase with and therefore compensates for that of the thermosteric effect (Figure 5), resulting in a small annual cycle (Figure 3). It was further concluded that in these places the halosteric effect occurs substantially over the 100–300 m depth (Figure 9), presumably due to interactions between the Labrador Shelf Water and the Gulf Stream Water (Mclellan, 1957; Csanady and Hamilton, 1988). Further offshore, the relative role of the halosteric effect increases poleward, consistent with the finding of Antonov *et al*. (2012).

3.2 Coastal and Shelf Variability

Along the coast and over the continental shelf, there is relatively high (about 5 cm) sea level variability from the south Labrador to Eastern Newfoundland (Figure 2).

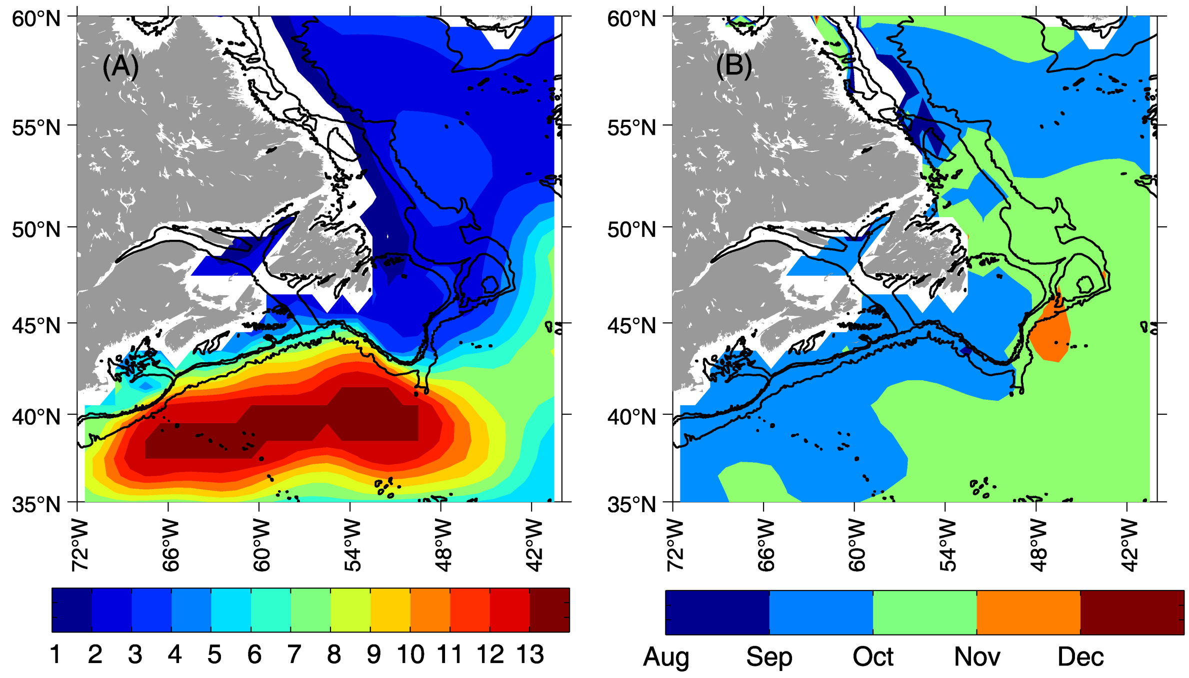

Figure 5. Same as Figure 2 but forthermosteric height based on Ishii *et al.* (2006) and Ishii and Kimoto (2009) 1° by 1° temperature and salinity dataset.

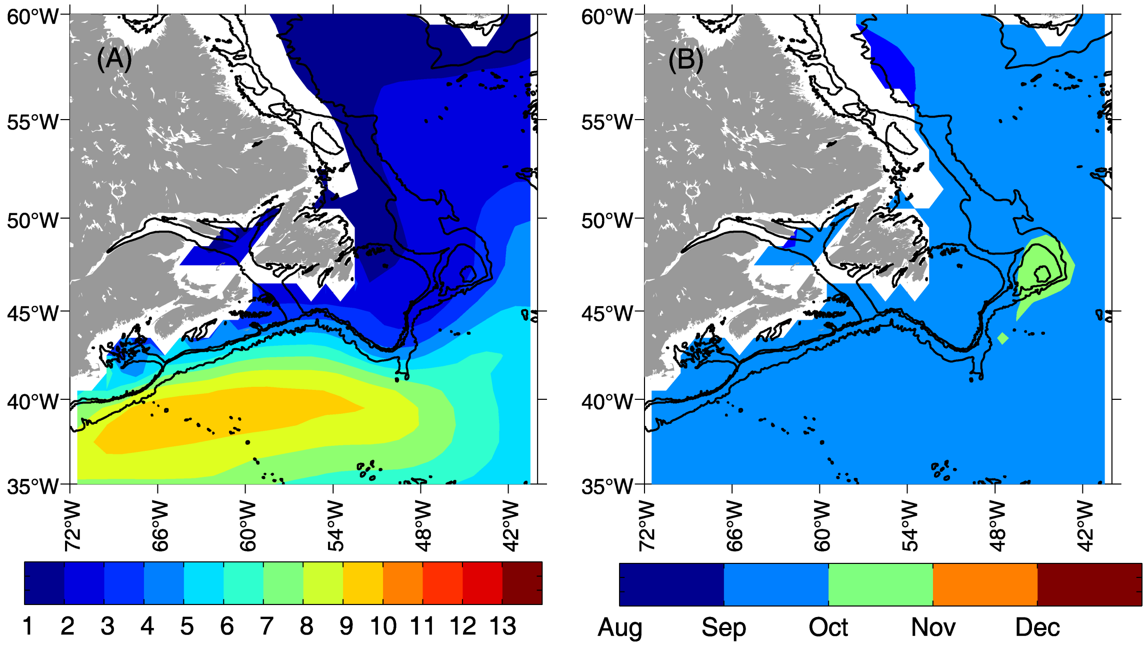

Figure 6. Same as Figure 5 but for thermosteric height over the top 100 m.

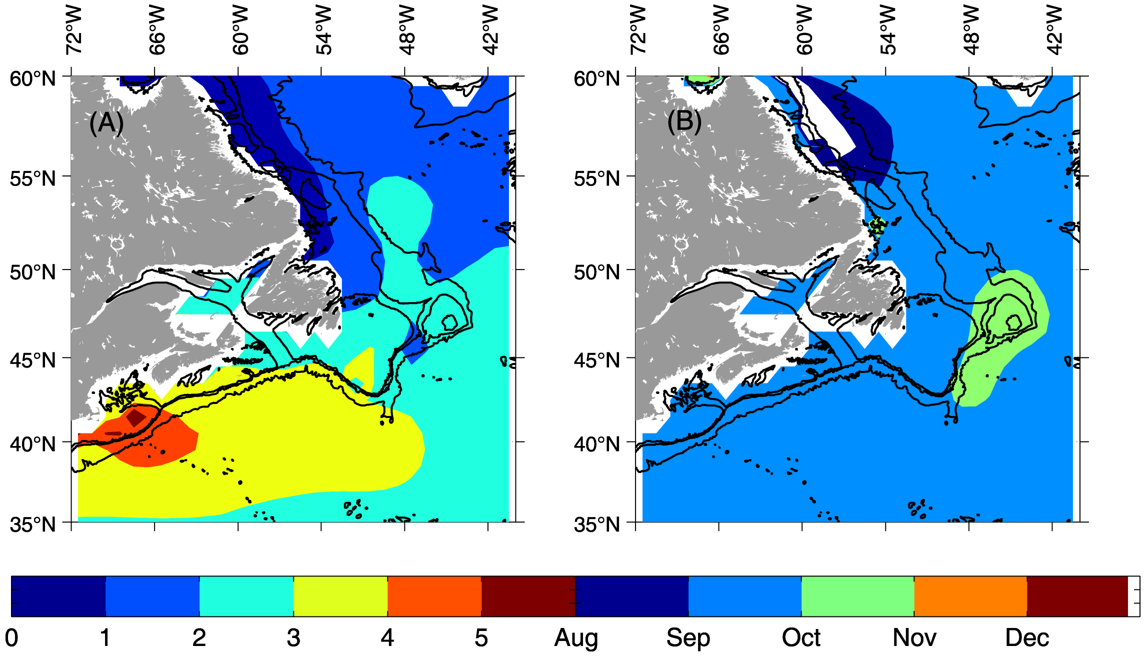

Figure 7. Same as Figure 6 but fortemperature (°C) averaged over 0-100 m, based on Ishii *et al.* (2006) and Ishii, Kimoto (2009) 1° by 1° temperature and salinity dataset.

The annual cycle was also relatively large off northeastern Nova Scotia. The annual sea level variability was small along and in the vicinity of the shelf edge of the northeastern and southeastern Newfoundland Shelf, with an amphidrome like minimum at 311°E, 48°N. Other areas of low annual cycle were the outer Laurentian Channel and the Gulf of Maine. In contrast, the phase pattern was highly coherent along the Canadian Atlantic coasts. This indicates that the annual sea level is higher in November from the South Labrador, to Newfoundland to Nova Scotia coasts.

Altimeter results and steric heights were interpolated onto coastal tide-gauge stations (Figure 1) along the Canadian Atlantic coasts. A comparison of the

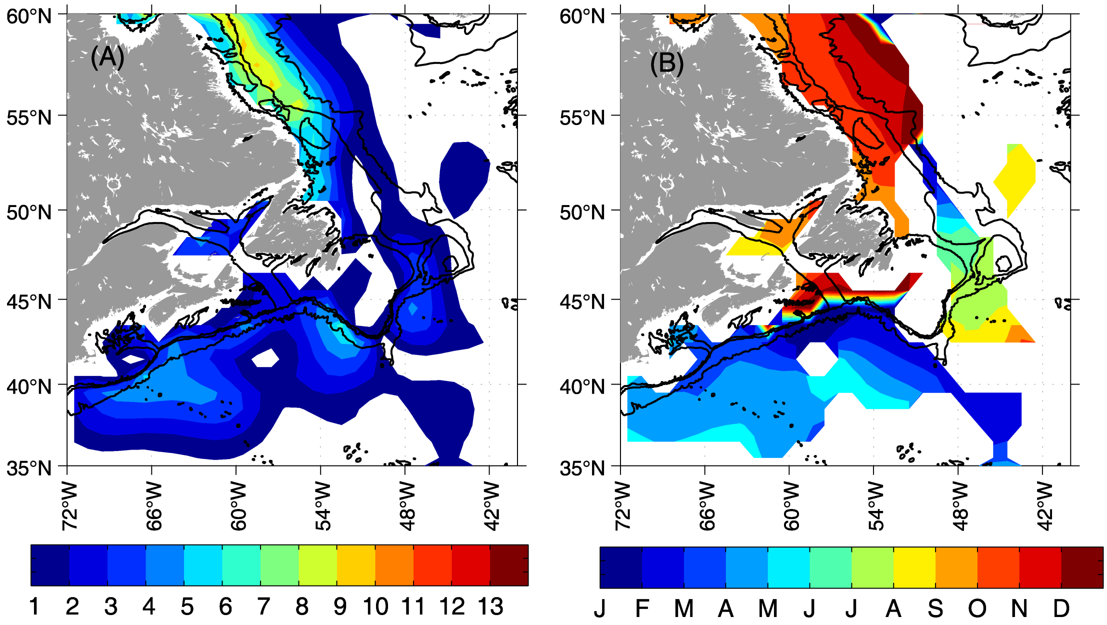

Figure 8. Same as Figure 2 but for halosteric height based on Ishii *et al.* (2006) and Ishii, Kimoto (2009) 1° by 1° temperature and salinity dataset.

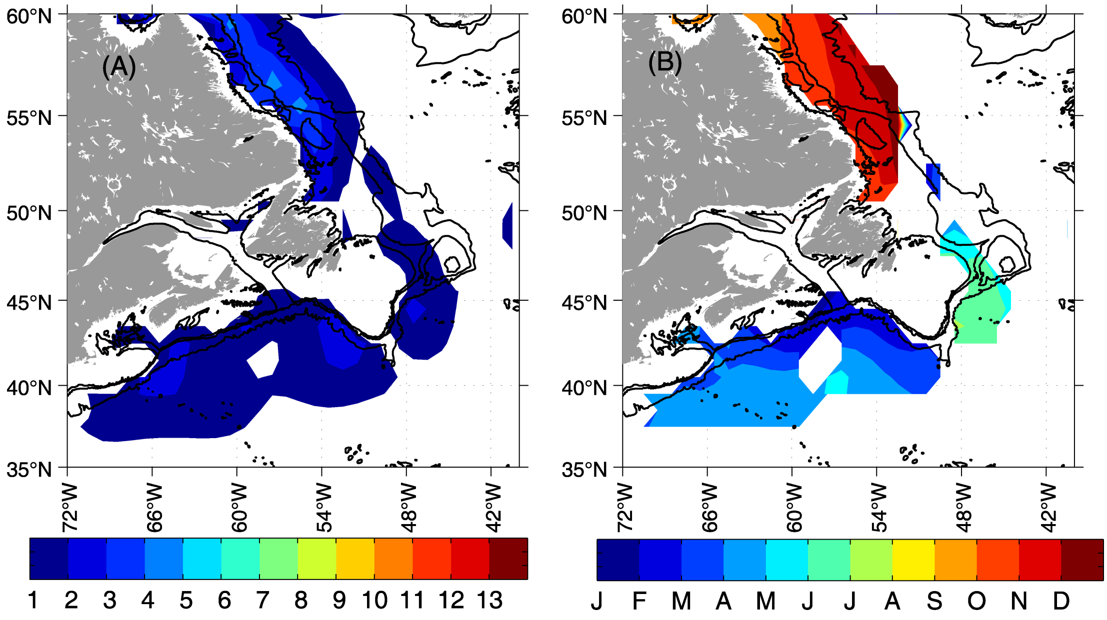

Figure 9. Same as Figure 8 but for halosteric height over the 100–300 m water column.

altimetric annual cycle with tide-gauge measurements indicates approximate agreement in amplitude and phase. While the mean differences for the annual cycle between tide-gauge and altimetric results were negligible, the RMS differences for amplitude and phases are 1.1 cm and 15 days, respectively (Table 2).

Steric height was compared with tide-gauge data and there were significant phase differences. The steric height was highest in September at most sites (Table 2), about two months earlier than the tide-gauge sea level (Table 2), mainly due to the temperature differences. The difference suggests that factors other than temperature/salinity changes may be important too. For example, using linear barotropic ocean models, Greatbatch *et al.* (1989) and Han (2005) indicated that the seasonal sea level variability at St. John's can approximately be accounted for by a linear combination of steric height and sea level response to the large-scale North Atlantic wind stress variability.

4. Conclusions

Investigation of sea level variations in the northern Northwest Atlantic was performed using the merged altimeter observations (Ducet, Le Traon and Reverdin, 2000), a temperature and salinity dataset (Ishii, Kimoto, Sakamoto *et al.*, 2006; Ishii and Kimoto, 2009), and tide-gauge data.

The present analysis revealed that a general south-to-north weakening of the annual sea level cycle in the deep ocean, from 4 cm in the central Labrador Sea to 15 cm in the Gulf Stream region. The sea level was higher on September/October in the deep ocean. The annual cycle in the deep ocean can approximately be accounted for by the steric height variability relative to 700 m. The thermosteric effect was generally the dominant contributor to the annual sea level cycle. The halosteric effect was dominant over the northern Labrador Slope. The halosteric effect over the Scotian and Newfoundland Slope is in magnitude smaller than and in phase opposite to the thermosteric effect and therefore substantially reduces the total steric effect. The thermosteric effect occurs mainly in the top 100 m water column, while the halosteric effect was substantial in the 100–300 m water column.

There was significant difference in the annual sea level variations between the deep and coastal oceans. The annual sea level cycle along the Canadian Atlantic coast showed significant change in amplitude, but the phase was highly coherent. High sea level occurs in fall. The steric height can account for a substantial portion of the coastal annual cycle, but other factors such as wind-forcing barotropic effect may be significant along the coasts of Newfoundland and Nova Scotia (Greatbatch, deYoung, Goulding *et al.*, 1989; Han, 2005). A baroclinic model may help better understand dynamics underlying the annual sea level cycle and explain its spatial differences.

Conflict of Interest

No conflict of interest was reported by all authors.

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References

Antonov J I, Levitus S and Boyer T P. (2002). Steric sea level variations during 1957–1994: Importance of salinity, *Journal of Geophysical Research*, 107(C12): SRF 14-1–SRF 14-8. http://dx.doi.org/10.1029/2001JC000964.

Archiving, Validation and Interpretation of Satellites Oceanographic data n.d., viewd 15 November, 2015, <http://www.aviso.oceanobs.com/en/altimetry/index.html>

Csanady G T and Hamilton P. (1988). Circulation of slopewater, *Continental Shelf Research*, 8(5–7): 565–624. http://dx.doi.org/10.1016/0278-4343(88)90068-4.

Ducet N, Le Traon P Y and Reverdin G. (2000). Global high resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and -2, *Journal of Geophysical Research*, 105(C8): 19477–19498. http://dx.doi.org/10.1029/2000JC900063.

Fu L L and Cazenave A. (Eds.) (2001). *Satellite Altimetry and Earth Sciences: A Handbook of Technique and Applications*, Academic Press: Cambridge, Massachusetts.

Greatbatch R J, deYoung B, Goulding A *et al.* (1990). On the influence of local and North Atlantic wind forcing on the seasonal variation of sea level on the Newfoundland and Labrador Shelf, *Journal of Geophysical Research. 95* (C4): 5279–5289. http://dx.doi.org/10.1029/JC095iC04p05279.

Han G. (2002). Interannual sea level variations in the Scotia-Maine region in the 1990s, Canadian *Journal of Remote Sensing*, 28(4): 581–587. http://dx.doi.org/10.5589/m02-056.

Han G. (2004). Sea level and surface current variability in the Gulf of St. Lawrence from satellite altimetry, *International Journal of Remote Sensing*, 25(22): 5069–5088. http://dx.doi.org/10.1080/01431160410001709039.

Han G. (2005). Wind-driven barotropic circulation off Newfoundland and Labrador, *Continental Shelf Research*, 25(17): 2084–2106. http://dx.doi.org/10.1016/j.csr.2005.04.015.

Han G. (2007). Satellite observations of seasonal and interannual changes of sea level and currents over the Scotian Slope, *Journal of Physical Oceanography*, 37(4): 1051– 1065. http://dx.doi.org/10.1175/JPO3036.1.

Han G, Tang C L and Smith P C. (2002). Annual variations of sea surface elevations and currents over the Scotian Shelf and Slope. *Journal of Physical Oceanography*, 32(6): 1794–1810. http://dx.doi.org/10.1175/1520-0485(2002)032<1794:AVOSSE>2.0.CO;2.

Ishii M, Kimoto M, Sakamoto K *et al.* (2006). Steric sea level changes estimated from historical ocean subsurface temperature and salinity analyses. *Journal of Oceanography*, 62(2): 155–170. http://dx.doi.org/10.1007/s10872-006-0041-y.

Ishii M and Kimoto M. (2009). Reevaluation of historical ocean heat content variations with time-varying XBT and MBT depth bias corrections, *Journal of Oceanography*, 65(3): 287–299. http://dx.doi.org/10.1007/s10872-009-0027-7.

Jet Propulsion Laboratory California Institute of Technology n.d., viewed 15 November, 2015, <http://grace.jpl.nasa.gov/data/get-data/monthly-mass-grids-ocean>

McLellan H J. (1957). On the distinctness and origin of the slope water off the Scotian Shelf and its easterly flow south of the Grand Banks, *Journal of the Fisheries Research Board of Canada*, 14(2): 213–239. http://dx.doi.org/10.1139/f57-011.

North American Regional Reanalysis n.d., viewed 15 November, 2015, <http://www.esrl.noaa.gov/psd/data/20gridded/data.narr.monolevel.html>

Petrie B and Anderson C. (1983). Circulation on the Newfoundland continental shelf, *Atmosphere-Ocean*, 21(2): 207–226. http://dx.doi.org/10.1080/07055900.1983.9649165.

Permanent Service for Mean Sea Level n.d., viewd 15 December, 2015, < http://www.psmsl.org/>

Vignudelli S, Kostianoy A, Cipollini, P *et al*. (Eds.) (2011). *Coastal Altimetry*, Springer-Verlag: Berlin Heidelberg.