Evaluation of W_0 in Canada using tide gauges and GOCE gravity field models

Research Article

T. Hayden^{1*}, E. Rangelova¹, M. G. Sideris¹ and M. Véronneau²

¹ Department of Geomatics Engineering, Schulich School of Engineering, University of Calgary, 2500 University Drive NW, Calgary, AB, T2N 1N4, Canada

² Geodetic Survey Division, Natural Resources Canada, 615 Booth Street, Ottawa, Ontario, K1A 0E9, Canada

Abstract:

The existing Canadian Geodetic Vertical Datum of 1928 (CGVD28) does not meet the needs of the modern user in terms of accuracy and accessibility. As a result, Canada plans to implement a geoid-based and global navigation satellite system (GNSS)-accessible vertical datum by 2013. One of the primary concerns in realizing this new vertical datum is to determine a W_0 value that will represent the potential of the zero height surface. The objective of this study is to evaluate W_0 by averaging the potential of points on the mean sea water surface utilizing tide gauge recordings and gravity field and steady-state ocean circulation explorer (GOCE)-based global geopotential models. In order to assess the performance of the GOCE-based models for the computation of W_0 , the models are extended with the high resolution gravitational model *EGM2008*. Regional gravimetric geoid models are also used for the estimation of W_0 . Additionally, local sea surface topography models are utilized in order to validate the W_0 results at the tide gauges. Excluding the Arctic coast, the W_0 values obtained from both tide gauges and oceanic sea surface topography models are not statistically different from the International Earth Rotation and Reference Systems Service (IERS) 2010 global conventional value $62636856.00 \text{ m}^2/\text{s}^2$.

Keywords:

GOCE • mean sea level • sea surface topography • vertical datum • W_0

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1. Introduction

The Geodetic Survey Division (GSD) of Natural Resources Canada (NRCan) has indicated that the existing Canadian Geodetic Vertical Datum of 1928 (CGVD28), which is currently the official vertical datum of Canada, will be replaced with a geoid-based and global navigation satellite system (GNSS)-accessible vertical datum by 2013, CGVD2013 (Smith et al. 2013, Ince et al. 2012). The U.S. National Geodetic Survey (NGS) plans to do the same though its implementation will not be until 2022 (NGS 2008). The move to a geoid-based vertical datum is motivated by the fact that the CGVD28 does not satisfy the needs of the modern datum in terms of accuracy and accessibility for precise height determination. The CGVD28 (Cannon

1929) was established by spirit levelling over the last one hundred years, forming a network of more than 80,000 benchmarks that connect over 120,000 km of levelling lines (Véronneau and Héroux 2006). The coverage of this first order levelling network is most densely distributed in the southern region of Canada, with sparse coverage in the Canadian North. Since the mid-1990s, NRCan reports that there has been a steady decline in the maintenance of this network, with only minimal targeted levelling performed since 2001 in order to support global and regional geoid model validation. The adoption of a geoid-based and GNSS-accessible vertical datum (i.e., CGVD2013) promises to overcome the limitations caused by existing distortions due to systematic errors and blunders in the CGVD28, reduce the cost of maintaining and expanding the existing first order levelling network, and offer full coverage of the Canadian territory.

Additionally, geoid modelling has improved with the use of recent satellite gravity missions, Challenging Mini-Satellite Payload

*E-mail: ttzaman@ucalgary.ca

(CHAMP; Reigber et al. 2002), Gravity Recovery and Climate Experiment (GRACE; Tapley et al. 2004), and Gravity field and steady-state Ocean Circulation Explorer (GOCE; Drinkwater et al. 2003), offering unprecedented precision in determining the long and medium wavelength components of the geoid. Specifically, the European Space Agency's (ESA) GOCE mission, launched on March 17, 2009, is expected to determine gravity anomalies upon its completion with an accuracy of 1 mGal and the geoid with an accuracy of 1–2 cm while achieving a spatial resolution of 100 km. One of the key factors in the implementation of the geoid-based vertical datum in Canada is to have a common datum with the USA, and thus a common geoid model for North America. Therefore, one of the primary concerns in choosing a common geoid model is to jointly agree upon which of the infinitely many surfaces of equal gravity potential will be chosen, i.e., which W_0 value should be chosen as the zero height surface. The determination of the W_0 for the new Canadian vertical datum is therefore the focus of this paper.

The W_0 value can be evaluated by averaging the potentials of points on the mean water surface, which can be computed from the mean sea surface topography that is referenced to an equipotential surface with a known potential. The sea surface topography can be obtained by three methods: 1) combining tide gauge recordings and a geoid model, 2) satellite altimetry sea surface heights and a geoid model, and 3) oceanic models. Generally, sea surface topography models are estimated from satellite altimetry and geodetic measurements, but may also include measurements such as sea water temperature, salinity data, tide gauge observations, and ocean surface drifter velocities (e.g., Rapp and Wang 1994, Ekman and Mäkinen 1996, Rio et al. 2004, Bingham and Haines 2006, Thompson and Demirov 2006, Foreman et al. 2008, Anderson and Knudsen 2009, Maximenko et al. 2009, Thompson et al. 2009, among others). In the literature, W_0 has largely been computed globally (excluding the polar regions) using satellite altimetry observations (e.g., Burša et al., 1998; Sánchez 2009). To a lesser extent, the geopotential at tide gauges has also been used to determine regional W_0 (e.g. Grafarend and Ardalan 1997, Ardalan et al. 2002).

For North America, NRCan/GSD and NGS have already adopted the W_0 value of 62636856.00 m²/s², which has been determined by averaging the potential values at selected North American tide gauges (Roman and Weston 2012). Our study focuses on the contribution of the Canadian tide gauges for the evaluation of W_0 with respect to the local mean sea level using sea level data that have been averaged over 19 years with the effects of sea level rise and vertical land motion accounted for. The use of a satellite-only global gravity field model, such as GOCE, is preferred. However, the effect of the omission errors of the satellite only model may be significant at the tide gauge locations along the Canadian coasts and may bias the mean potential of the local mean sea level. Thus, quantifying the approximate omission errors resulting from GOCE-only global geopotential models for the evaluation of W_0 is a focus of this paper. For this reason, W_0 is also computed with the use

of high resolution gravity field models such as *CGG2010* (Huang and Véronneau, 2013) and *EGM2008* (Pavlis et al. 2012), and regional oceanic sea surface topography models.

2. Experimental Procedures

The basic procedure for computing a W_0 value through tide gauge averaging can be outlined as follows:

1. Selection of tide gauges which have been surveyed with GNSS;
2. Selection of a geoid model;
3. Computation of the gravity potential W of the local mean sea level height at each respective tide gauge; and
4. Computation of W_0 as the mean W value from all the tide gauges.

The following section gives an overview of the data used in the determination of the W_0 value for Canada using the averaging of tide gauge data to determine the mean sea level around the Canadian coasts.

2.1. Data

The local sea surface topography (SST) at each respective tide gauge must be evaluated in order to find the potential of the local mean sea level (MSL). The main datasets needed are water level data at tide gauges, geoid undulations from global geopotential models or regional geoid models, and ellipsoidal heights of tidal benchmarks from GNSS. Moreover, W_0 can also be evaluated from oceanographic sea surface topography models, and W_0 obtained from these models can be used to validate results obtained from the tide gauge averaging.

2.1.1. Tide Gauges

In order to obtain a W value that best represents the MSL around the Canadian coastline, a near uniform distribution of tide gauge sites with up to date long-term time series, preferably up to one lunar nodal cycle (i.e., approximately 19 years) or multiples of this cycle, would be ideal. This is due to the fact that tide gauge recordings over a time period shorter than 18.6 years will not lead to the evaluation of the MSL according to its rigorous definition (i.e., the MSL is the zero-frequency component of sea level variation (Ardalan and Safari 2005)). Hence, the determination of MSL requires the removal of all periodic constituents existing in the tide gauge record, where the longest constituent is the lunar nodal tidal constituent of 18.6 years. Moreover, the 19-year data span will also average out effects of sea levels due to weather such as wind stress, changes in atmospheric pressure, and storm events (Pugh 1987). For the scope and objectives of this study, tide gauges in the Canadian Pacific, Atlantic, and Arctic coasts were selected for the determination of the mean W_0 value based on the following criteria:

Figure 1. Geographical distribution of tide gauges in Canada used for W_0 computation (Red: Tide gauge stations with data gaps Black: Tide gauge stations without data gaps).

1. The tide gauge has a corresponding benchmark which has been surveyed with GNSS;
2. The tide gauge benchmark should be in good condition according to the Canadian Hydrographic Service (CHS); and
3. The tide gauge has water level data for 19 years from 1992 to 2011 without significant data gaps (i.e., no more than 2-3 years of missing data).

With these criteria, only a small portion of tide gauges were suitable candidates for the determination of W_0 . Specifically, the Arctic region of Canada was grossly under-represented, with only one station satisfying the above criteria. In order to extend the analysis, especially to the Arctic, tide gauges with at least 12 months of data after 1990 were also included, and the local MSL was computed from monthly water level data obtained from the CHS. The MSL for tide gauges with 19 years of data was evaluated by first averaging daily water levels to monthly time series, and then from monthly to annual time series, and lastly the 19-year average was computed. For time series with less than 24 days in a month, the monthly averages were interpolated from neighbouring values (using the nearest neighbour value if only one monthly sea level value was available, or the average of the two nearest neighbour values if two monthly sea level values were available). If the time series had more than 24 days of water level records, the monthly averaged value was computed with the number of daily records available. Similarly, the monthly time series with five or more months of missing data for annual averages were also interpolated from neighbouring values where possible. The final list of stations used is given in Table 1 and the geographic distribution of the tide gauges is given in Fig. 1. There are 38 tide gauges in total, but only 23 of these tide gauges have a full 19-year water level time series. Specifically, there are 12 tide gauges in the Pacific, 10 tide gauges in the

Atlantic, and 1 tide gauge in the Arctic that contain 19 years of water level data.

2.1.2. Global Geopotential Models and Regional Geoid Models

Global geopotential models (GGMs) are required in order to obtain the gravity potential at the tide gauge sites. A satellite-only model that is globally consistent is preferred as it will provide a field to which the averaged Canadian MSL potential can be connected, and it also avoids inconsistencies included in the terrestrial gravity anomalies due to the use of different height datums. There are two main factors that affect the accuracy of the spherical harmonic expansions. The first is the accuracy of the satellite data, which consist of data errors that propagate into the spherical harmonic coefficients; this is known as commission error and is computed from the error variance-covariance matrix of the GGM. The second is the omission error, i.e., the gravity field signal omitted from the GGM due to the use of a maximum degree (n_{max}) of spherical harmonic expansion. In practice, the omission error of the satellite-only gravity field models will affect the determination of the potential at each tide gauge, and since the W_0 is based on the averaging of these potential values, the effect of the omission error on W_0 is an important factor to be investigated due to the limited number of tide gauges available. For that reason, regional geoid models based on terrestrial gravity and terrain data are also included in the analysis.

This study focuses on the use of third generation GOCE models (i.e., *go_cons_gcf_2_tim_r3* (*tim_r3*), *go_cons_gcf_2_dir_r3* (*dir_r3*), and *goco03s*) as they perform better than the previous generations of GOCE models due to the fact that they contain 12 months of GOCE data compared to the 2 or 6 months in the previously released models. For a full summary and description of the available GGMs one may refer to the International Centre for Global Earth Models (ICGEM) website: <http://icgem.gfz-potsdam.de/ICGEM/>. A complete description about different methods used in the development of GOCE-based models can be found in Pail et al. (2011).

2.1.3. Sea Surface Topography Models

Three regional sea surface topography models have been utilized in order to validate the mean W_0 results obtained from tide gauge averaging. The first model, developed by M.G.G. Foreman at the Department of Fisheries and Oceans Canada (DFO), covers the North-East region of the Pacific Ocean (Foreman et al. 2008). The other two models are for the northern Atlantic Ocean. These models were developed by D. G. Wright from DFO and K. R. Thompson and E. Demirov from Dalhousie University (Thompson and Demirov 2006). The Foreman model is a variable density model, with the SST nodes being quite dense along the coast and sparse for the deep ocean. The grid spacing for the Wright model is approximately 15 arc minutes, while the grid spacing for the Thompson & Demirov model is approximately 20 arc minutes. All models are given in the mean-tide system. Figure 2 shows the geographic dis-

Table 1. Canadian tide gauge stations and local mean sea levels.

Tide Gauge Station	Latitude (°) ITRF2008	Longitude (°) ITRF2008	MSL (m) at Epoch 2008.0
PACIFIC REGION WITH 19 FULL YEARS OF WATER LEVEL DATA			
7120	48.4240	-123.3710	1.9201
7277	48.6536	-123.4515	2.3137
7795	49.3370	-123.2530	3.1190
8074	50.0420	-125.2470	2.8931
8408	50.7220	-127.4890	2.9059
8615	49.1540	-125.9130	2.0909
8735	50.5130	-128.0290	2.2238
9850	53.2520	-132.0720	3.9944
7735	49.2870	-123.1100	3.0982
8545	48.8360	-125.1360	2.0464
8976	52.1630	-128.1430	2.8757
9354	54.3170	-130.3240	3.9098
PACIFIC REGION WITH DATA GAPS			
7130	48.4237	-123.3027	2.0277
8215	50.3980	-125.9610	2.9197
8525	48.5550	-124.4210	2.0477
ATLANTIC REGION WITH 19 FULL YEARS OF WATER LEVEL DATA			
612	46.2167	-60.2500	0.8276
835	47.3000	-53.9833	1.3773
1700	46.2333	-63.1167	1.7657
2000	47.0833	-64.8833	0.8164
2330	48.9970	-64.3805	1.0384
2780	50.1948	-66.3768	1.5838
2985	48.4783	-68.5137	2.2687
365	43.8333	-66.1167	2.5976
490	44.6667	-63.5833	1.0551
65	45.2510	-66.0630	4.4707
ATLANTIC REGION WITH DATA GAPS			
491	44.6833	-63.6167	1.0728
665	47.5667	-59.1333	1.1971
990	48.6510	-53.1150	0.6083
1430	56.5500	-61.6833	1.4182
1680	45.9500	-62.7500	1.4391
1805	46.2270	-64.5460	1.2319
1970	47.3789	-61.8573	0.9209
2145	47.9000	-65.8500	1.3714
ARCTIC REGION WITH 19 FULL YEARS OF WATER LEVEL DATA			
5010	58.7667	-94.1833	2.5972
ARCTIC REGION WITH DATA GAPS			
3765	82.4919	-62.3173	0.4558
3980	67.5167	-64.0667	0.7834
6380	70.7363	-117.7612	0.3886
6485	69.4382	-132.9944	0.4467

tribution of the SST nodes for the Foreman, Thompson & Demirov, and the Wright regional SST models.

The mean sea surface topography represents the separation between the mean sea surface and an equipotential surface (Foreman et al. 2008), i.e., the surface of zero motion which is assumed to be represented by the geoid. Therefore, it is essential to know the potential of the geoid surface that was used in the regional SST models. For all three SST models, this surface approaches a value of $62636856.00 \text{ m}^2/\text{s}^2$. This value can be estimated by uti-

lizing the methodology presented in the next section (see Eq. 3) by subtracting the SST obtained from the oceanic models from the mean water level computed from the tide gauge records with the use of either a global geoid model or a regional geoid model with a known reference potential. Other methods include comparing the SST values from the oceanic models with those obtained from satellite altimetry and a geoid model with known reference potential. One may also use a modified version of the methodology generally used to compute local vertical datum offsets (e.g. Burša

Figure 2. Regional oceanic models with SST values in meters (Top Left: Foreman Top Right: Wright Bottom: Thompson & Demirov).

et al. 2004, Kotsakis et al. 2011) where ellipsoidal heights are replaced with sea surface heights (SSH) and orthometric heights are replaced with SST values obtained from the oceanic models.

2.2. Methodology

For this study, the potential of a point (W_P) on the mean water surface was computed from the mean SST (i.e., based on a time averaged sea surface, where the periodic effects of the tides are averaged out), which is referenced to an equipotential surface with a known potential W_N . The SST is the separation between the MSL and the geoid and can be approximated by the following (Sánchez 2009):

$$SST_P = \frac{W_N - W_P}{\gamma_P}, \quad (1)$$

where W_N is the potential of the geoid (the equipotential surface) and γ_P is the normal gravity computed at the geoid with the latitude of the computational point. Based on the geometrical evaluation of the SST from Fig. 3, the SST at a tide gauge can be expressed as

$$SST = h - N - CD + Z_0, \quad (2)$$

where h is the ellipsoidal height of the tidal benchmark, N is the geoid height, CD is the height of the tidal benchmark above the

chart datum, and Z_0 is the height of the local MSL above the chart datum. Equation (2) can be evaluated using either a tide-free system, mean-tide system, or zero-tide system. A tide-free quantity will have the total tidal effects removed, though in practice such a quantity is not fully realizable. Based on the IERS 2010 convention (Petit and Luzum 2010), it is recommended to use a zero-tide system for geopotential quantities in order to eliminate the external component of the permanent tide, and a mean-tide system that eliminates the periodic variations of the tidal effects for quantities relating to station positions. In our computations the tide-free system has been adopted for the sake of convenience as h and N were given in a tide-free system. The SST in Eq. (3) is converted to a potential difference, which is subtracted from the potential of the equipotential surface W_N . Thus, from Eq. (1) and Eq. (2) the potential at point P can be computed from the following equation:

$$W_P = W_N - [(h - N - CD + Z_0) \gamma_P]. \quad (3)$$

The mean potential of the water surface (i.e., W_0) is computed by the means of the least-squares solution of the system of observation equations evaluated by (3), which is simply the average of all the W_P computed at each tide gauge for equally-weighted observations.

Equation (3) describes the case if the SST is evaluated from tide gauge data. On the other hand, if a SST model is used to compute

W_P by means of the following equation

$$W_P = W_N - (SST_P \gamma_P), \quad (4)$$

one has to ensure that the SST models are converted from a mean-tide system to a tide-free system. This conversion is given in Eq. (5) below (Ekman 1989, Mäkinen and Ihde 2009):

$$SST_{TF} = SST_{MT} + 0.68 [9.9 - (29.6 \sin^2 \varphi)] 0.01, \quad (5)$$

where SST_{MT} is the sea surface topography given in the mean-tide system, and φ is the latitude of the SST node from the model. In order to compare the W_0 values obtained from tide gauges and those obtained using sea surface topography models, the SST from the ocean models have been converted to a tide-free system. The difference between using a mean-tide and a tide-free system is $0.5 \text{ m}^2/\text{s}^2$. Using the 3-sigma test, this difference is smaller than three times the formal error, thus it does not result in statistically different W_0 values.

When W_0 is evaluated from SST models, the mean potential is obtained by a weighted average as shown in Eq. (6):

$$W_0 = \frac{\sum (W_{P_i} \cos \varphi_i)}{\sum (\cos \varphi_i)}, \quad (6)$$

where W_{P_i} is the potential of the water surface estimated from a SST node in the model, and φ_i is the latitude of the SST node from the model. It should be noted that Eq. (6) does not comply with the Gauss-Listing definition of the geoid (Gauss 1828, Bessel 1837, Listing 1873), and therefore can only be considered an approximation. In order for Eq. (6) to comply with the Gauss-Listing definition of the geoid (i.e., the equipotential surface of the gravity field of the Earth that best coincides with the global mean sea level), the weighting should be changed from $\cos \varphi_i$ to $1/\gamma_i$. The $\cos \varphi_i$ term assigns less weight to higher latitude terms reflecting the fact that SST accuracy decreases with latitude as many SST models assimilate altimetry data; however using $1/\gamma_i$ in place of $\cos \varphi_i$ yields essentially the same results (i.e., differences are on the order of $0.01 \text{ m}^2/\text{s}^2$ and this results in a 1 mm error in SST).

Before evaluating Eq. (3), the values for h , CD , and Z_0 were all brought to the same epoch of 2008.0. However, for the Pacific region, the CHS did not have epoch information for the chart datum, so the CD values were left as originally given in the data files obtained by NRCan. Additionally, the CHS did not have complete epoch information for the chart datum in the Atlantic region, thus the epoch information of the nearest available tide gauge was utilized if this information was missing for a particular station. In order to bring the epoch of all the necessary values to 2008.0, both sea level rise and vertical land motion had to be taken into account for the chart datum and the MSL estimated at each tide gauge. Only the vertical land motion correction had to be applied for the ellipsoidal height of the tidal benchmark. The absolute sea level rate

Figure 3. Geometrical evaluation of sea surface topography at tide gauges.

used was the 20th century average for North America: $1.8 \text{ mm/yr} \pm 0.2 \text{ mm/yr}$ (Church et al. 2004, Snay et al. 2007, Mazzotti et al. 2008). For the Pacific region, the vertical land motion rates are mainly due to seismic variations, and these values were obtained from the GNSS-based rates evaluated by Mazzotti et al. (2008). For the Atlantic and Arctic region, the vertical land motion rates are primarily due to post-glacial rebound, and these values were interpolated at the tide gauge locations from the Argus and Peltier (2010) *GEODVEL1b* GPS solution.

3. Results

The Canadian tide gauges have been split into three different regions: Pacific, Atlantic, and Arctic in order to validate results with those computed from SST models, as the SST models have a variable density of nodes. For example, the Foreman model is more densely distributed than the Wright and Thompson & Demirov models, which will cause the mean W_0 value to be biased as there are more SST nodes in the Pacific than in the Atlantic. All computations have been implemented with the GRS80 ellipsoidal parameters.

3.1. W_0 Value Evaluated with GOCE Models Expanded to Degree and Order 180

It is known from model evaluation studies (e.g., Ince et al. 2012, Hirt et al. 2012) that the GOCE models perform well only up to degree and order 180. In this section, the three third generation GOCE models are used up to degree and order 180, and are spectrally enhanced with *EGM2008* (Pavlis et al. 2012) from degree 181 to 2190 in order to study the effect of the omission error. In the ideal case, as the W_0 is a single averaged value mainly dependent on low-frequency spectral content, the effect of the omission error is not expected to be significant. However, as mentioned previously, the effect of the GOCE omission error may be significant at the tide gauges. Table 2 shows the W_0 results with the full 19 years of water level data using tide gauges in the Pacific, Atlantic, and a combination of tide gauges in the Pacific and Atlantic. The stan-

dard deviations are estimated by the a posteriori variance factor of the adjustment of Eq. (3) using a unit weight matrix, and as such the error estimates shown in the table indicate only a formal statistical accuracy. The GOCE+EGM2008 spectrally enhanced models contain higher frequency content compared with the GOCE only models that results in smaller residuals, which reduces the formal standard deviation of the estimated W_0 value. All results presented in this section are based on Eq. (3).

The third generation direct model *dir_r3* uses the *itg-grace2010s* as a background model and the combination model *goco03s* is also based on 7 years of GRACE data (Bruinsma et al. 2010, Mayer-Gürr et al. 2012 available at <http://www.goco.eu/>). One may refer to Pail et al. (2010) for information regarding the first generation GOCE+GRACE combination model *goco01s*. The main difference between *goco03s* and *goco01s* is that the third generation model uses a longer time series of GOCE observations and uses data from complementary sources in addition to GRACE. The third generation time-wise model *tim_r3* is the only pure GOCE model as it does not depend on any background model (Pail et al. 2011). From Table 2 it is evident that the three GOCE models perform similarly. For example, the W_0 value using *tim_r3* is $62636855.44 \text{ m}^2/\text{s}^2$, the mean potential using *goco03s* is $62636855.19 \text{ m}^2/\text{s}^2$, and the mean potential using *dir_r3* is $62636855.39 \text{ m}^2/\text{s}^2$. The separation between these equipotential surfaces is 2.5 cm at most.

As seen from the results with the extended models, the mean W_0 is close to $62636854.00 \text{ m}^2/\text{s}^2$ for the Pacific and $62636859.00 \text{ m}^2/\text{s}^2$ for the Atlantic. For example, when *goco03s* is spectrally enhanced with *EGM2008*, the W_0 value is $62636854.18 \text{ m}^2/\text{s}^2$ for the Pacific, while for the Atlantic region the value is $62636859.21 \text{ m}^2/\text{s}^2$. The potential decreases in the Pacific as the SST for this region is mostly positive, which is also verified by the local SST model for this region (Foreman et al. 2008). For the Atlantic region, the SST is for the most part negative, thus it is reasonable for the potential to increase with respect to the W_N surface used in Eq. (3). Sturges (1967) reported this separation of the MSL on the Pacific and Atlantic coasts in North America. MSL values at tide gauges on the Pacific coast appeared to be systematically 60-70 cm higher than those of similar latitude on the Atlantic coast.

For the Pacific region, the effect of the omission error for all the models averages to $1.59 \text{ m}^2/\text{s}^2$ or approximately a 16 cm difference when the satellite only models are compared with the spectrally enhanced models. For the Atlantic region the effect of the omission error averages to $0.92 \text{ m}^2/\text{s}^2$ (or 9 cm). Lastly, the effect of the omission error for the combined Pacific and Atlantic tide gauges averages to be $1.29 \text{ m}^2/\text{s}^2$ (or 13 cm).

The W_0 computed using the spectrally enhanced models for the combination of Pacific and Atlantic tide gauges averages to $62636856.62 \text{ m}^2/\text{s}^2$. This dataset is the most robust as the MSL has the tide effects and variability due to weather averaged out. Of course, the limitation of this data set is that the Arctic region is ex-

cluded from the analysis. If the Arctic stations are included, one would expect the potential to increase, as the tide gauges in the Arctic have a negative sea surface topography. However, it would not be desirable to include these stations as they have significant data gaps in their water level time series.

As there are no published results available for W_0 for North America from tide gauge averaging, we can only compare our results from those computed at NRCan. For the Pacific, NRCan obtained a W_0 value of $62636852.34 \text{ m}^2/\text{s}^2$ using 15 tide gauges and the *tim_r3* GOCE model and for the Atlantic a value of $62636858.98 \text{ m}^2/\text{s}^2$ using 19 tide gauges and the *tim_r3* GOCE model (Véronneau 2012). These values are consistent with those computed using *tim_r3* only in Table 2. NRCan obtained a W_0 value of $62636856.79 \text{ m}^2/\text{s}^2$ from a total of 39 tide gauges including the Arctic tide gauges (Véronneau 2012). This accounts for a 14 cm difference in the mean level surface computed in Table 2 (i.e., $62636855.44 \text{ m}^2/\text{s}^2$) for the combination of the Pacific and Atlantic tide gauges when compared to the value computed by NRCan. In addition to the different number of tide gauges used, other factors such as the treatment of the tide gauge records data and the truncation degree of the GOCE model contribute to this difference.

3.2. W_0 Value Evaluated with Regional Gravimetric Geoid Models

In this section, results for W_0 evaluated with Eq. (3) using geoid undulations from regional gravimetric geoid models are presented. *CGG2010* is the official geoid model for Canada developed by NRCan. On the other hand, the gravimetric model developed by Ince et al. (2012) can be considered as an updated model for Canada using the third generation direct GOCE model (i.e., *dir_r3*) for the long wavelength contributions of the gravity field. Both *CGG2010* and the model developed by Ince et al. (2012) can be considered high resolution geoid models as they both include terrestrial gravity and topography data in order to model the high frequency components of the gravity field. The *CGG2010* differs in that it uses the *goco01s* model in order to account for the long wavelength components of the gravity field in addition to *EGM2008* (Huang J., Natural Resources Canada, personal communication, Nov. 29, 2012). As both gravimetric geoid models use the same terrestrial data to model the high frequency contributions of the gravity field, it is expected that they will perform similarly when evaluating W_0 and they are also expected to perform consistently with the spectrally enhanced GOCE+EGM2008 models of the previous section. Hence, the gravimetric geoid models in this section provide another measure of the difference in performance of the GOCE only models and that of the high resolution gravity models when evaluating W_0 from tide gauge averaging.

The results from Table 3 are consistent with those results utilizing the spectrally enhanced GOCE models with *EGM2008* shown in Table 2. This is expected as the *EGM2008* model also utilizes terrestrial data in order to account for medium to short wavelength contributions of the gravity field (Pavlis et al. 2012). The results computed using the gravimetric geoid models help to further

Table 2. W_0 values for Pacific, Atlantic, and Pacific + Atlantic tide gauges with 19 years of water level data with GGMs expanded to degree 180 and 2190 (add 62636800.00 m^2/s^2 to values in table).

GGM Model	Pacific	Atlantic	Pacific + Atlantic
goco03s	52.59 ± 2.13	58.30 ± 1.16	55.19 ± 1.39
$n_{\max}:180$			
goco03s+EGM2008	54.18 ± 0.13	59.21 ± 0.16	56.47 ± 0.56
$n_{\max}:180+181 \text{ to } 2190$			
tim_r3	52.84 ± 2.13	58.56 ± 1.17	55.44 ± 1.40
$n_{\max}:180$			
tim_r3+EGM2008	54.43 ± 0.12	59.48 ± 0.19	56.73 ± 0.56
$n_{\max}:180+181 \text{ to } 2190$			
dir_r3	52.78 ± 2.16	58.51 ± 1.20	55.39 ± 1.41
$n_{\max}:180$			
dir_r3+EGM2008	54.38 ± 0.19	59.43 ± 0.19	56.67 ± 0.56
$n_{\max}:180+181 \text{ to } 2190$			

Table 3. W_0 values for three Canadian regions computed with regional gravimetric geoid models (add 62636800.00 m^2/s^2 to all values).

Geoid Model	CGG2010	Ince et al. (2012)
Pacific tide gauges with 19 years of water level data		
Mean W_0 (m^2/s^2)	54.25 ± 0.13	54.17 ± 0.11
Atlantic tide gauges with 19 years of water level data		
Mean W_0 (m^2/s^2)	59.67 ± 0.23	59.60 ± 0.19
All Arctic tide gauge stations (5 Stations)		
Mean W_0 (m^2/s^2)	60.15 ± 0.17	60.19 ± 0.28
Pacific and Atlantic tide gauges with 19 years of water level data		
Mean W_0 (m^2/s^2)	56.71 ± 0.60	56.64 ± 0.60
Pacific and Atlantic tide gauges with 19 years of water level data + All Arctic tide gauges		
Mean W_0 (m^2/s^2)	57.35 ± 0.56	57.30 ± 0.56
All tide gauges (38 Stations)		
Mean W_0 (m^2/s^2)	57.44 ± 0.47	57.38 ± 0.46

highlight the fact that simply utilizing the GOCE models truncated at degree and order 180 is not sufficient for determining W_0 from tide gauge averaging as the omission error affecting the potential at each tide gauge could be potentially large, which will affect the W_0 determination due to the limited number of gauges available.

The two gravimetric geoid models yield very consistent results when compared with each other. For example, the W_0 value computed using *CGG2010* for the Pacific region is $62636854.25 \text{ m}^2/\text{s}^2$ while for the Atlantic region it is $62636859.67 \text{ m}^2/\text{s}^2$, and for the Arctic region the W_0 value averages to $62636860.15 \text{ m}^2/\text{s}^2$. When utilizing the model developed by Ince et al. (2012), the W_0 value for the Pacific is $62636854.17 \text{ m}^2/\text{s}^2$, for the Atlantic it is $62636859.60 \text{ m}^2/\text{s}^2$, and it is $62636860.19 \text{ m}^2/\text{s}^2$ for the Arctic. The differences in the W_0 values range from $0.04 \text{ m}^2/\text{s}^2$ to $0.08 \text{ m}^2/\text{s}^2$, which is well within the range of three times their formal errors that vary from $0.3 \text{ m}^2/\text{s}^2$ to $0.8 \text{ m}^2/\text{s}^2$. Thus, the W_0 values estimated using *CGG2010* and Ince's model can be considered statistically similar.

3.3. W_0 Value with Sea Surface Topography Models

W_0 can also be computed from SST models using Eq. (4) and Eq. (6). These models can help to validate the results of the previ-

ous two sections. Table 4 presents the mean W_0 computed for the Pacific region using the Foreman model and for the Atlantic using the Wright and the Thompson & Demirov models. The table shows the breakdown of results for a region closer to the coast and then for that of the deeper ocean, as well as results for SST interpolated to the specific tide gauge sites in order to validate the results from tide gauge averaging. When using the SST models, the standard deviations are computed as the standard deviation of the sample using Eq. (6).

The results verify the positive SST found in the Pacific and the negative SST found in the North Atlantic (see Fig. 2), and generally validate the trends seen from the tide gauge averaging. The W_0 value using the Foreman model approaches $62636854.00 \text{ m}^2/\text{s}^2$ for the Pacific. For example, for the Pacific coastal region the W_0 is $62636854.32 \text{ m}^2/\text{s}^2$ while the W_0 value computed with SST interpolated to the Pacific tide gauge sites is $62636854.38 \text{ m}^2/\text{s}^2$. Similarly, for the Atlantic coast using the Wright model the W_0 value is $62636859.46 \text{ m}^2/\text{s}^2$ while the Thompson & Demirov model yields a potential of $62636861.34 \text{ m}^2/\text{s}^2$. Using SST values interpolated to tide gauges with full 19 years of water level data, the W_0 value for the Atlantic using the Wright model yields $62636858.99 \text{ m}^2/\text{s}^2$, and the W_0 value using the Thompson & Demirov model yields $62636858.54 \text{ m}^2/\text{s}^2$. The mean national W_0 evaluated with the

Table 4. W_0 for the Pacific and Atlantic regions computed with local SST models (add 62636800.00 m^2/s^2 to values in table).

SST Model	Foreman (Pacific)	Wright (Atlantic)	Thompson & Demirov (Atlantic)
Pacific Coast: 45 °N to 60 °N and 130 °W to 115 °W Atlantic Coast: 45 °N to 60 °N and 81.5 °W to 57 °W			
Mean W_0 (m^2/s^2)	54.32 $\pm$ 0.62 (70602 Points)	59.46 $\pm$ 2.53 (2983 Points)	61.34 $\pm$ 1.29 (1076 Points)
Pacific: 45 °N to 60 °N and 140 °W to 115 °W Atlantic: 45 °N to 60 °N and 81.5 °W to 45 °W			
Mean W_0 (m^2/s^2)	54.33 $\pm$ 0.64 (83991 Points)	61.84 $\pm$ 3.07 (7126 Points)	62.90 $\pm$ 2.01 (3634 Points)
SST interpolated for tide gauge sites with 19 full years of water level data			
Mean W_0 (m^2/s^2)	54.38 $\pm$ 0.65	58.99 $\pm$ 0.48	58.54 $\pm$ 0.52
SST interpolated for tide gauge sites with 19 full years of water level data (Pacific & Atlantic)			
Mean W_0 (m^2/s^2)	–	56.55 $\pm$ 0.81 (Foreman & Wright)	56.33 $\pm$ 0.83 (Foreman & Thompson)
SST interpolated for all Canadian tide gauge sites			
Mean W_0 (m^2/s^2)	54.42 $\pm$ 0.60	59.02 $\pm$ 0.88	59.39 $\pm$ 1.10
SST interpolated for all Canadian tide gauge sites (Pacific & Atlantic)			
Mean W_0 (m^2/s^2)	–	56.98 $\pm$ 1.07 (Foreman & Wright)	57.14 $\pm$ 1.25 (Foreman & Thompson)

SST interpolated to the Pacific and Atlantic tide gauges with full 19 years of water level data yields 62636856.55 m^2/s^2 for the Foreman and Wright combination while it yields 62636856.33 m^2/s^2 for the Foreman and Thompson & Demirov combination. However, when all the tide gauge sites are included in the analysis, the potential increases to approximately 62636857.00 m^2/s^2 as can be seen from Table 4 for the Foreman and Wright combination, which yields 62636856.98 m^2/s^2 . The Foreman and the Thompson & Demirov combination yields 62636857.14 m^2/s^2 .

To summarize the results from sections 3.1 to 3.3, the estimated W_0 value is not statistically different from the IERS 2010 value of 62636856.00 m^2/s^2 (Petit & Luzum, 2010) provided that the Arctic region is excluded from the analysis. Nevertheless, one has to keep in mind that the IERS 2010 value has a global representation while section 3 gives regional results for Canada. Based on Table 5, which shows the main results obtained from sections 3.1 to 3.3 using tide gauge averaging and SST models, it can be seen that the difference in the W_0 potential between the IERS 2010 value and those computed in sections 3.1 to 3.3 are less than three times their formal errors. As the Canadian Geodetic Vertical Datum of 2013 (CGVD2013) datum plans to adopt 62636856.00 m^2/s^2 for W_0 , it is evident from the results presented in Tables 2–4 that the MSL on the Pacific coast averages to be approximately 17–18 cm above the CGVD2013 datum, while it will be 37–38 cm below the CGVD2013 datum in the Atlantic, and the MSL will be approximately 43 cm below the CGVD2013 datum in the Arctic.

4. Discussion and conclusions

The objective of the paper was to evaluate W_0 from tide gauge averaging and SST models within the context of realizing a new geoid-based and GNSS-accessible vertical datum for Canada in order to replace the outdated CGVD28. One of the main goals of the paper was to assess the performance of the third generation GOCE models for the purpose of computing W_0 in Canada. This was done by evaluating the SST at tide gauges utilizing the three third generation GOCE models truncated at degree and order 180, as above this degree and order the commission error of the models

increase significantly. Due to the small number of tide gauges, concentrated on the Atlantic and Pacific coasts, available for the evaluation of W_0 , it was expected that the omission error of the GOCE-only models may have a large effect on the computed W_0 value. In order to test this, the GOCE models were spectrally extended with the high resolution gravity model *EGM2008* from degree 181 to 2190. Also, the performance of the GOCE only models was compared with that of two other high resolution regional geoid models: *CGG2010* and the regional gravimetric geoid model developed by Ince et al. (2012). It was shown that the omission error averages to 16 cm in the Pacific and 9 cm in the Atlantic, and averages to 13 cm when both Pacific and Atlantic tide gauges are utilized. The second goal of the paper was to validate the results of tide gauge averaging utilizing SST models—similar results were found for both the Pacific and Atlantic coasts whether W_0 was evaluated using SST models or tide gauge averaging.

Factors that affect the quality of the tide gauge data include: data gaps in the water level time series, missing epoch information for the chart datums on both the Pacific and Atlantic coasts, interpolation errors for epoch information for the chart datums, interpolation errors for determining post-glacial rebound velocities at tide gauges, and utilizing MSL values that are based on time series shorter than 19 years. In terms of validating the tide gauge averaging results, the main factor that would affect the W_0 value is the interpolation error of the SSTs at the tide gauges.

In order to find the W_0 of the local MSL, one needs a 19-year water level time series (or some multiple of this) to fulfill the definition of the MSL as being the zero-frequency component of sea level variation. If using shorter time series, the variations due to tide and weather may not average out and may be propagated into W_0 . Thus, the requirement of the 19-year average MSL limits the number and the distribution of tide gauges available for determining W_0 at the Canadian coasts. However, shorter time series may be utilized in order to increase the number of tide gauges available, so as to improve the distribution, although in such a case the W_0 value will not reflect properly the potential of the local MSL. Data gaps have been avoided as best as possible by interpolating values from

Table 5. Summary of W_0 results using 19 years of water level data for Canada using Pacific and Atlantic tide gauges and SST interpolated from oceanic models (add 62636800.00 m^2/s^2 to values in table).

Method	W_0 (m^2/s^2)
Tide Gauge Averaging GOCE only (goco03s)	55.19 ± 1.39
Tide Gauge Averaging GOCE+EGM2008 (goco03s+EGM2008)	56.47 ± 0.56
Tide Gauge Averaging with Gravimetric Geoid CCG2010	56.71 ± 0.60
SST Model (Foreman + Thompson & Demirov)	56.33 ± 0.83

neighbouring ones. It is not expected that this will significantly affect the results of W_0 as the MSL values have been averaged from daily to monthly to annual, and finally to 19-year time series averages. In most cases, when updating the epoch of the chart datum to 2008.0, it is only a matter of a few millimetres to one centimetre difference, and as such the height of the tidal benchmark (i.e., CD in Eq. (3)) will not be significantly affected due to different epochs or interpolation errors. Most importantly, the W_0 value is not expected to be significantly affected by missing chart datum information as the geoid is a smooth surface and W_0 is obtained by averaging. This applies similarly for the post-glacial rebound rates as the annual velocities are of the order of millimetre; the effect in the final W_0 computation was not significant.

Since the tide gauges used are specific to Canada only (American tide gauges were not included in the study), the potentials obtained from tide gauge averaging cannot be considered an average for all of North America. Certainly this limitation can be overcome by utilizing SST models to compute W_0 instead of tide gauges. Moreover, the Arctic region lacks SST models, as well as sufficient water level data. Therefore this region cannot be included when computing W_0 , which biases the results primarily to the Pacific and Atlantic coasts in the southern region of Canada. As seen from the results, the mean potential based on tide gauge averaging will be greater than the standard IERS (2010) global value if Arctic tide gauges are to be implemented in the analysis. For this reason, the difference in W_0 results obtained in this study using tide gauge averaging or SST models and the value adopted by NRCAN and NGS are not statistically significant. It can be seen from Fig. 2 that the SST along the Canadian coastline does not differ much from the SST along the US coastline, with the exception of the Gulf region. In terms of including the deep sea SST values, the potential for the Canadian portion of North America will be greater than that of the USA portion of North America due to the fact that the Northern Atlantic and the Arctic has colder waters and negative SST while the Atlantic along the American east coast has warmer waters due to Gulf Stream, which creates positive SST (see Fig. 2). The main consequence of adopting the IERS 2010 value is that it represents an average over the entire North American continent; it will not reflect the potential of the local MSL along the coast in Canada.

The climate-related change in the mean sea level, i.e., addition of melt water from Greenland, Alaska glaciers, and Canadian ice caps, and the possible expansion of the ocean due to warming of the ocean surface, also affects the W_0 value. Even though, these ef-

fects can influence the W_0 value over a decade and longer, the adopted value for North America is essentially a convention, and not necessarily the exact value of the coastal mean sea level for North America. Until there are longer time series of water level data available for the Arctic, one may use the mean W_0 value computed from Pacific and Atlantic tide gauges with 19 years of water level data as the zero-level height surface for Canada, and this value is close to the global IERS (2010) value of 62636856.00 m^2/s^2 . Certainly, from the SST model interpolated values from Table 5 one can see that the values approach the global IERS 2010 potential value (i.e., 62636856.33 m^2/s^2 for the Foreman and Thompson & Demirov combined models), and from tide gauge averaging using the spectrally enhanced GGM models such as the *goco03s+EGM2008* the national average potential is 62636856.47 m^2/s^2 . Though the W_0 value of the spectrally enhanced GGMs and the regional gravimetric geoid models when utilizing the Pacific and Atlantic tide gauges with full 19 years of water level data seem to be approximately 0.60 m^2/s^2 greater than the global IERS value, the standard deviations of these results show that they cannot be considered statistically different.

Finally, it has been shown that the truncation degree of the GOCE models is important. In particular, when comparing the GOCE only models with the regional gravimetric geoids that utilize GOCE and GRACE data to model the long wavelength contributions of the gravity field, it has been shown that the high frequency contributions from the terrestrial data yield W_0 values that are consistent only with the spectrally enhanced GOCE+EGM2008 models. Hence, we can conclude that the truncation degree and order of 180 is not adequate when evaluating W_0 from scattered tide gauge points in Canada as the higher frequency contribution of the gravity field is not properly modeled. Additional future work includes computing the W_0 value using future GOCE models expanded to their maximum degree and order provided that a full variance-covariance matrix of the spherical harmonic coefficients are propagated in order to evaluate geoid undulations at each tide gauge as accurately as possible. Our initial investigations for this future work show that when the GOCE models are expanded to their maximum degree and order, the effect of the omission error on the potential evaluated at a tide gauge may still be significant. However, the effect of the omission error on the averaged W_0 seems to be negligible for well distributed stations, indicating that the use of a satellite-only global geopotential model may be sufficient for the computation of W_0 in regions with very good coverage and distribution of tide gauge or GNSS levelling benchmarks.

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