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Subsidence and Relative Sea Level Rise in the Fraser River Delta, Greater Vancouver, British Columbia, from Combined Geodetic Data

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1. ABSTRACT

We use two independent methods to map the spatial variations in vertical motion of the land surface in the Greater Vancouver Regional District: 1) first-order geodetic levelling in 1958/1959 and 1977, and 2) satellite-based Coherent-Target-Monitoring Interferometric-Synthetic-Aperture RADAR (CTM-InSAR) over the period 1992-1999. The first-order geodetic levelling involves over 60 benchmarks and the CTM-InSAR over 300,000 ground targets. Vertical velocities at five permanent Global Positioning System sites, together with 37 other sites in British Columbia and Washington, are used to align the levelling and CTM-InSAR results to the ITRF2000 global reference frame. The combined analysis shows an average subsidence rate in the Holocene delta (Richmond and Delta municipalities) of 1-2 mm/yr compared to uplift of 0-1 mm/yr in the Pleistocene Highlands (Vancouver, Burnaby, Surrey, Tsawwassen Heights). Areas of subsidence coincide with recent (post-glacial) Fraser River Delta sedimentation but there is no significant correlation with known variations in sediment thickness. Localized rapid subsidence areas (> 4 mm/yr) appear to be associated with sites of relatively recent construction. The BC Ferries Terminal at Tsawwassen, for which historical levelling data and CTM-InSAR are available, exhibits subsidence rates that have diminished from 15 mm/yr in the 1960's and 1970's to 3 mm/yr in the 1990's. More work is needed to determine the effects of the age and size of engineering structures on the observed vertical velocities. The land subsidence map is tied to regional sea level using a subset of collocated tide gauges and GPS stations. This analysis points to a regional Northeast Pacific sea-level rise of 1.8 mm/yr over the 20th century. In contrast, the local tide gauges at Point Atkinson and Vancouver show a low regional sea-level rise of 0.3 mm/yr when combined with our geodetic results. We conclude that the two local gauges are problematic and should not be used for sea-level rise analysis, unless a physical reason for the low rates can be found. Based on the Intergovernmental Panel on Climate Change global predictions, we estimate a future relative sea-level rise (sea-level increase + subsidence) by 2100 of 40-70 cm for most of the Fraser River Delta, and possibly as much as 130 cm in areas that are subsiding rapidly.

2. INTRODUCTION

Like most coastal cities, Greater Vancouver, British Columbia, faces significant societal and economic hazards due to global sea-level rise. Several of its component communities are built on the Fraser River Holocene delta and could experience relative sea-level (RSL) rise enhanced beyond the expected global mean, due to significant ongoing subsidence of the deltaic surface. The Fraser River delta is a topographically flat area of unconsolidated Holocene sediments containing the municipalities of Delta and Richmond (Fig. 1). Holocene delta sediments were deposited over an irregular Pleistocene erosion surface extending to a depth of up to 300 m (Hunter and Christian, 2001) (Fig. 2). The land surface is on average at or near sea level and is protected by a system of dykes. Ongoing subsidence of the deltaic surface increases the rates of relative sea-level rise and impacts offshore and inter-tidal bio-sedimentological processes. Relative settlement in the Fraser delta of up to 13.7 cm was reported in the early 1960's from repeated precise levelling of geodetic benchmarks over the 39-year interval 1919-1958 (Lilly, J.E., reported in Mathews and Shephard, 1962). Present-day variations in vertical motions at the decimeter to centimeter level may be expected, given the variations in sediment loading history inland from the delta front, the variations in thickness of the Holocene sediments, and the variations in thickness of the underlying Pleistocene unit. Britton et al. (1995) show that the depth to Tertiary bedrock beneath the delta varies between 200 and 1000 m below surface. It is unknown whether other factors, such as the depth and concentration of natural gas beneath the delta (Pullen et al., 1998), could play a role in modifying subsidence rates. Moreover, the Tertiary bedrock surface itself may be deforming on a regional scale in response to tectonic activity or postglacial rebound.

We use two independent methods to map the variations in vertical motion of the land surface in the Greater Vancouver Regional District (GVRD), including the Holocene delta : 1) first-order geodetic levelling in 1958/1959 and 1977, and 2) satellite-based interferometric synthetic aperture RADAR (InSAR) data from the Earth Resources Satellites 1 and 2 (ERS-1 and ERS-2) from 1992 to 1999. These methods provide information on relative vertical movement rates. Referencing these rates to sea level requires detailed comparison with available tide gauge and Global Positioning System (GPS) data in the GVRD. In this report, we make a preliminary attempt to reference the vertical movement results to sea level using knowledge of relative sea-level rates at regional and local tide gauges and estimates of absolute vertical land velocity from analysis of continuous GPS sites.

3. COHERENT TARGET MONITORING INTERFEROMETRIC SAR

Interferometric Synthetic Aperture RADAR (InSAR) is a recently developed remote-sensing geodetic technique that involves combining repeated satellite RADAR scenes of a given area. The scenes are processed to form interferograms measuring changes in phase delay of pulses back-scattered from relatively stable, slowly moving angular objects on the ground (cf. review in Bürgmann et al., 2000). Coherent movements of the Earth's surface in the line of sight of the satellite can be detected from scene to scene at the centimeter level, after correction for other sources of signal delay and noise such as topography, satellite orbit uncertainty, atmospheric delay, etc. One of the main applications of InSAR in solid Earth sciences is to image ground displacements at the centimeter to decimeter level associated with earthquakes (e.g., Massonet et al., 1993). In the last few years, new InSAR analysis techniques (so-called "persistent scatterer" techniques) involving the combination of numerous interferograms acquired over several years has lead to a detection capability of surface movements of a few mm/yr (e.g., Ferretti et al., 2001, van der Kooij, 2002, Hooper et al., 2004). These techniques are based on the identification and monitoring in a stack of interferograms of particularly phase-stable pixels through time. The phase histories of these pixels are transformed to produce line-of-sight or vertical velocity maps. These InSAR techniques work particularly well over urban areas, where buildings and other structures provide coherent stable targets.

3.1. Data availability and processing

In this study, we use 51 repeated scenes from the European RADAR satellites ERS1 and ERS2 collected over the GVRD between April 1992 and June 1999, allowing the computation of 35 interferograms. We use the Coherent Target Monitoring method (CTM, van der Kooij, 2002) to detect slow uplift and subsidence motions at the millimeter per year level. The CTM method used here does not assume a motion model in order to filter the data at the early stages of the analysis. Hence, the essential motion information is not compromised. Details of a typical, non-specific CTM analysis are provided in Table 1. Several iterations of the phase-coherence calculation procedure allow for an optimal target detection and coverage of the study area. A reference area of about 1 km x 1 km is selected in the southern Vancouver highland and is arbitrarily forced to zero displacement through the series of interferograms.

The phase time series of over 350,000 coherent pixels in the GVRD are analyzed using a least-square linear regression. The principal focus of this study is the determination of steady vertical motions and their implications for local subsidence and relative sea-level rise over the next century. Thus, rapid transient responses to recent changes, such as new building loads, have been rejected from the final results. For each pixel time series, we produce a short-term velocity time series by estimating the velocity over a 2-year window centered on each data point (Fig. 3). We define an arbitrary "velocity threshold" of 30 mm/yr as an indicator of rapid non-steady behavior in parts of the time series. Pixels with rapid transient changes are removed from the rest of the analysis. Approximately 14% of the pixels are eliminated in this way.

3.2. Results

The CTM-InSAR map covers the GVRD over an area about 50 km east-west by 40 km north-south (Fig. 4). We obtain results mostly over urban areas, where buildings and other structures provide phase-stable backscatter targets. Blank areas are associated with forested zones (e.g., Burn's Bog in Delta, Stanley Park in Vancouver, the south-eastern part of the University of BC Endowment Lands in Point Grey) and farms (eastern Richmond, most of Delta, parts of Surrey and most of Langley Township). In these vegetated areas, the lack of coherent reflecting targets precludes the estimation of displacements using the CTM-InSAR technique.

The maps of vertical velocity and associated uncertainty over the GVRD (Figs. 4 and 5) are produced by running a 100 m-radius circular moving-average window over the whole area. This final step allows for a small level of low-pass filtering by smoothing of individual large values not representative of the steady regional behavior. The CTM-InSAR map clearly shows that the Holocene delta (Municipalities of Richmond and Delta) is subsiding at rates of about 1-2 mm/yr relative to the highland reference area. In contrast, the Pleistocene uplands show a small uplift of 0-1 mm/yr.

Several locations, a few hundred meters to about a kilometer in size, are affected by higher subsidence rates of 3-6 mm/yr. Some of these are known sites of recent construction and may thus represent load-induced increased compaction (e.g., the Deltaport, the

Vancouver International Airport). Other areas, such as Annacis Island or the center of Lulu Island, may be representative of fast local compaction of the thick (100-200 m) Holocene sediment sequence (Fig. 3). Standard delta compaction models predict a general increase in subsidence with sediment thickness (e.g., Meckel et al., 2007). However, a first-order comparison between Holocene sediment thickness from borehole data (Hunter and Christian, 2001) and subsidence rates averaged within a 200 m-radius of the borehole sites shows no obvious correlation. The relation between Holocene sediment lithology and thickness, compaction rates, and subsidence rates needs to be addressed in more detail in further studies.

Note that small (~ 100 m), isolated features in the CTM-InSAR map, particularly rapid uplift (red) features, should be treated with caution unless verified by other measurements.

4. VERTICAL MOVEMENT FROM GEODETIC LEVELLING

We obtain an independent assessment of relative vertical motion in the GVRD from geodetic levelling surveys, which have been successfully used to determine vertical crustal movements in many areas of Canada (e.g., Vanicek and Nagy, 1981; Lambert et al., 1986; Dragert et al., 1994). First-order geodetic levelling in the B.C. Lower Mainland, including the Fraser River delta, was carried out by the Geodetic Survey Division, Natural Resources Canada, at four main epochs (1919, 1958/59, 1966/67 and 1977) as part of the maintenance of the Canadian Vertical Reference System. The 1966/67 survey came at the end of a very ambitious cross-Canada project that was poorly suited to crustal stability studies. The structure of the network in and around the Fraser delta and the specifications used in this survey compromised its usefulness for vertical movement studies. In addition, the rods used in the 1919 survey (metal-scale rods) were of “unknown” manufacture and there are indications from later calibrations that the two rods may have been “unstable” by today’s standards. For these reasons, we concentrate on the analysis of the 1958/59 and the 1977 surveys to determine changes in relative benchmark heights in and around the Fraser River delta over a 19-year period. Levelling data are also available for the Tsawwassen causeway for roughly the same period (1959-1978) and for a period near that of our InSAR study (1990-2002). These data illustrate the initial rapid subsidence of engineering structures built on the sediments of the Fraser delta, followed in subsequent years by the lower rates more typical of the natural compaction of recent deltaic sediments (Meckel et al., 2006, 2007).

4.1. Vertical Movements in the GVRD

4.1.1. Description of Available Data

Both the 1958/59 and the 1977 levelling networks exhibited good structure in the Fraser River delta and surrounding region and delivered 61 common benchmarks for determination of vertical crustal movement (Fig. 6). Both surveys were carried out according to first-order specifications with an expected closure between forward and backward levelling sections of less than 4 mm times the square root of the distance surveyed in kilometres, as described in the Geodetic Survey Division’s vertical control specifications manual (Surveys and Mapping Branch, 1978). These specifications result in a random error propagation along a typical line, where forward and backward levelling results are averaged, of less than 2 mm x Sq. Root (distance). The levelling data for both surveys were converted to Helmert orthometric heights using a common set of gravity values. The 1977 data were corrected for systematic effects due to refraction (Holdahl, 1981), rod scale error, and the effect of the Earth’s magnetic field on the Zeiss Ni1 instrument (Holdahl et al., 1986). No information is available for the 1958/59 survey to allow refraction and rod scale corrections to be made. Details on instruments used and corrections applied in the two surveys are summarized in Table 2.

4.1.2. Data Analysis Method and Results

After applying corrections for systematic errors in the 1977 survey, we analyze the data for each survey in a least-square, unconstrained adjustment, holding benchmark 19C159J fixed. We introduce a further stage of analysis where the benchmark heights and associated errors are expressed with respect to the mean height of all benchmarks in each of the two networks. This transformation provides a measure of error that is less dependent on the distance from the reference benchmark and facilitates the identification of significant changes in height between surveys. We determine that the mean height of the common benchmarks in the 1958/59 and 1977 networks with respect to mean sea level are 20.771 m and 20.776 m, respectively, differing by 5 mm. After first adding 5 mm to the 1958/59 heights to make the mean heights of the two networks coincide, we then calculate the relative changes in benchmark height between the two epochs. This gives the relative vertical movement between the two surveys. Changes between the two surveys with respect to the common network mean are shown in Table 3 and indicate a relative downward movement of ~ 60 mm of the outer Fraser River delta with respect to Burnaby. Assuming a constant rate of relative motion, we estimate relative subsidence rates of parts of Richmond -West with respect to Burnaby and Surrey of 2-3 mm/yr (Fig. 7). We note that 5 benchmarks out of 61 indicate anomalous subsidence (50 mm or greater) relative to the nominal reference level over the 19 year period. Four of these benchmarks are located on Lulu Island (Richmond). These high rates may coincide with local construction loading.

We estimate the error in the relative vertical movement rates from estimates of the random and systematic levelling errors in the measured height changes. Random errors in height change are estimated as part of the least squares adjustment process used in the analysis of the 1958/59 and 1977 surveys and combined systematic errors are estimated from errors associated with rod calibration and atmospheric refraction (Appendix 1). The random and systematic errors are combined geometrically to obtain a combined estimate of errors in observed height change over the 19 years between surveys. The resulting standard error on vertical movement rates are shown in Figure 8.

4.2. Vertical Movement of the Tsawwassen Causeway

4.2.1. Description of Available Data

Levelling by the Canadian Hydrographic Service along the Tsawwassen causeway (Site of the BC Ferries Corporation terminal) began in 1959/60 from a reference benchmark, BM 19-1959, located at Tsawwassen bluffs to benchmarks, BM 18-1959 and BM 1-1960, located beside the ferry slips (a distance of ~3 km). A third benchmark, BM 66C45, was added near the ferry slips in 1966. During the period 1959–1978, these benchmarks were levelled approximately eight times with respect to BM 19-1959 on the shore, and several local levelling lines within the BC Ferries complex were also carried out. All three benchmarks at the ferry slips appear to have been disturbed by construction in the winter of 1973/74 and were destroyed by 1979. A new benchmark, BM 77-C10, was established in 1977 beside the highway leading to the BC Ferries complex, ~1.5 km from the ferry slips. In 1990, five benchmarks were established by the BC Ferries Corporation (BCFC 10-90, BCFC 12-90, BCFC 13-90, BCFC 14-90, BCFC 16-90). The heights of these benchmarks were measured with respect to BM 77-C10 by Coast Pilot in 1990. All of these benchmarks were levelled by Canadian Hydrographic Service with respect to the shore reference, BM 19-1959, in 2002. The locations of the benchmarks at the BC Ferries complex are indicated in Figure 9.

4.2.2. Results

Benchmark heights with respect to the shore reference, BM 19-1959 are determined within first-order specifications, leading to a random error in differential heights of less than 3 mm. Since the levelling route is along flat terrain, systematic errors are expected to be negligible. Results from 1959 to 2002 are summarized in Figure 10, where changes in benchmark heights are plotted with respect to the onshore reference. We find an average subsidence rate of the southwest end of the BC Ferries complex of ~15 mm/yr over the first 20 years after initial construction (1959-1978). From 1990 to 2002, the subsidence rate in the same area (BM's BCFC 10-90, BCFC 14-90 and BCFC 16-90) has decreased to an average of 3.7 ± 0.9 mm/yr. However, the vertical subsidence rates vary in the complex over a range of 1.9 mm/yr (BM BCFC 12-90) to 5.2 mm/yr (BM BCFC 10-90) when all five bench marks are considered. BM 77-C10, located along the highway, outside the main complex, does not appear to have subsided with respect to the onshore reference benchmark.

4.3. Comparison of CTM-InSAR and levelling velocities

4.3.1. GVRD

Figure 11 shows InSAR rates versus the levelling rates for the entire study area, where InSAR rates are averaged over a 200 m-radius circular area centered on the levelling benchmarks. A Type 2 regression, taking both InSAR and levelling errors into account, indicates a correlation (slope) of 0.34 ± 0.06 and a coherence of 0.57, suggesting that the levelling rates are 3 times faster than the InSAR rates. The slope of the regression is significantly different from unity at the 99% confidence level. This discrepancy and the reduction in vertical rates with time observed on the Tsawwassen causeway (Fig. 10) points to a time-dependant construction loading issue that requires further investigation.

4.3.2. Tsawwassen Causeway

A number of InSAR coherent targets were identified on the Tsawwassen causeway (Fig. 12). Their locations and vertical rates are shown in relation to the levelling benchmarks on the causeway. InSAR rates near the ferry slips are about -2 mm/yr compared to targets on or near Tsawwassen bluffs of around 0 mm/yr. Other targets in the parking area show vertical velocities of -4 mm/yr or higher. Most of the targets having vertical velocities of -6 mm/yr or higher in the figure have been rejected on the grounds of non-steady behavior (cf. section 3.1). They are retained here to indicate the high spatial variability of vertical rates, probably as a result of construction loading during the 1990's. The undisturbed InSAR data, close to the levelling bench marks, indicate vertical subsidence of the BC Ferries terminal through the 1990's at rates from -2 to -4 mm/yr, in agreement with levelling rates ranging from -1.9 to -5.2 mm/yr.

5. GPS CALIBRATED SUBSIDENCE MAP

In the last decade, the Global Positioning System (GPS) has become a primary geodetic tool for measuring static and dynamic positioning at the centimeter to millimeter level. High-precision GPS analysis is widely used in the Solid Earth geophysics community to study processes as varied as surface deformation in response to groundwater withdrawal, earthquakes, or mountain building. We use GPS data available across the GVRD region as an independent tool to validate the results obtained by levelling and InSAR and to integrate these results in a global reference frame compatible with external data sets such as tide gauge measurements.

5.1. GPS data and analysis

Since mid 2002, the GVRD maintains a positioning control system that consists of 5 permanent GPS stations distributed over the whole region (Fig. 1). The primary purpose of this network is to provide positioning correction for legal surveys and centimeter-level real-time navigation needs. These GPS stations are not equipped with geodetic-quality monuments and are installed on the tops of public buildings. By comparison with geodetic-monument stations in southern British Columbia, the GVRD non-geodetic sites show similar low noise levels. The vertical daily root-mean-square scatter is about 2-3 mm and the annual cycle variation is about 1-4 mm. Thus, we consider the results from the GVRD sites to be as robust as more standard geodetic-monument sites.

Data for the five GVRD GPS sites are integrated with another 35 permanent GPS sites in southwestern Canada and northwestern USA and are processed at the Geological Survey of Canada, Sidney, as part of our crustal deformation monitoring service. The data are processed following a high-precision double-difference phase solution using the Bernese software in order to provide daily relative positions at a precision level of 1-5 mm (cf. Mazzotti et al., 2003). Velocities are relative to a reference station (DRAO, near Penticton, BC) and are derived by a least-square adjustment of the daily position time series that includes a linear trend (velocity), artificial and natural offsets (e.g., instrument change, earthquake), and a one-year seasonal signal.

GPS time series are characterized by a frequency-dependent noise with a spectral power of about 1-2 (Ma et al., 1999, Williams et al., 2004) that corresponds to flicker and random-walk noise. Noise analysis based on frequency-dependent models suggests that, for continuous time series of 1-year length, the uncertainties (standard error) on the horizontal and vertical velocity components are about 1-1.5 mm/yr and 5 mm/yr, respectively. For 5-year time series, the uncertainties decrease to about 0.5 and 1.5 mm/yr, respectively. For the GVRD sites, we use continuous data between December 2002 and November 2006 and apply a common-filter technique that reduces the daily scatter. The noise-model calibrated uncertainties on the vertical velocities are ~ 0.8 mm/yr.

The alignment of the GPS velocities in a global reference frame contributes another source of uncertainty. To align our local solution, we prescribe the velocity of the reference site (DRAO) as specified in the chosen reference frame. Formal uncertainties associated with DRAO velocity in individual frames are relatively small (< 0.5 mm/yr), but systematic uncertainties are a much larger source of error. The International Terrestrial Reference Frame (ITRF) is the standard choice for high-precision GPS studies. Since 2002, four realizations of the ITRF have been released: ITRF2000, IGS00, IGb00, and the most recent ITRF2005. The formal vertical velocity of DRAO varies between 0.8 and 1.7 mm/yr for those 4 realizations. Because of conflicting views as to which of these frames is the best or most appropriate (e.g., Ray et al., 2004; Argus, 2007), we use an average value of 1.2 mm/yr and propagate an extra uncertainty of 0.5 mm/yr to represent the possibility of systematic bias in the choice of the reference frame.

Another source of uncertainty, mostly specific to the vertical velocity components, is associated with GPS antenna phase center calibrations. Recent studies suggest that the use of relative phase center values might lead to biases in the vertical velocities of as much as 1 mm/yr (Ge et al., 2005).

5.2. GPS Results and comparison with InSAR vertical rates

The vertical velocities at the five GVRD GPS sites are shown in Table 4 and Figure 13. The velocities range between -1.8 and 1.0 mm/yr. The final standard errors, accounting for frequency-dependent noise (0.8 mm/yr), reference frame uncertainty (0.5 mm/yr), and antenna uncertainty (1.0 mm/yr), is 1.3-1.4 mm/yr. The sites in Vancouver (BCVC), Surrey (BCSF), Maple Ridge (MCMR), and Langley (BCLC) show a negligible vertical motion. These four sites are located in the Pleistocene highlands. In contrast, the site at Lulu Island (BCLI, Richmond) is located near the western edge of the Holocene delta and shows a subsidence of 1.8 ± 1.3 mm/yr, significant at the 67% confidence level.

CTM-InSAR velocities near the GPS stations are estimated by averaging the velocities of the pixels located within a 200-meter radius circle of the GPS site. Similarly, uncertainties (standard errors) on the average rates are defined by averaging the individual pixel standard error within the same radius. Comparison between the GPS and InSAR rates (Table 4 and Fig. 13) shows a very good agreement, with an average difference of 0.0 ± 0.5 mm/yr, well within the standard errors of both techniques. The largest difference (0.6 mm/yr) is found for the BCLI site, which is relatively poorly sampled by the CTM-InSAR results compared to the other sites (Fig. 4).

Based on the good agreement between the GPS and CTM-InSAR results and the lack of significant systematic offset between the two techniques, we conclude that the CTM-InSAR results are representative of absolute vertical velocities, i.e., velocities with respect to the ITRF2000. Although the standard errors on the relative InSAR rates (pixel to pixel) are about 0.5-1 mm/yr, the standard errors on the absolute rates are larger due to the uncertainties in the GPS reference frame alignment. We estimate the absolute InSAR standard error by adding geometrically the relative InSAR uncertainties and the 0.5 mm/yr uncertainty related to the GPS frame.

6. TIDE GAUGE AND RELATIVE SEA-LEVEL RISE

One of the main implications of local subsidence of the Fraser River delta is an increase in local relative sea-level rise. Steady subsidence of 1-2 mm/yr will contribute an additional 10 to 20 cm of extra relative sea-level rise in the next 100 years above the rise due to the regional oceanographic-only component.

6.1. Sea-level rise estimates

In its latest report, the Intergovernmental Panel on Climate Change (IPCC) estimates that the rate of global mean sea-level rise during the 20th century is estimated to be about 1.7 ± 0.5 mm/yr (Bindoff et al., 2007), with more specific studies suggesting an actual value in the higher end of this spectrum (Douglas, 2001). However, there are indications of potentially large spatial variations in sea-level rise from one region to another. Using a combination of tide gauge and satellite altimetry data, Church et al. (2004) suggest that regional sea-level rise in western BC may be as high as 2.5 mm/yr. A similar study by Cazenave et al. (2007) based on tide gauge and temperature data suggests similar or possibly higher regional values. In contrast, our preliminary results based on integrating collocated tide gauge and GPS data in southwestern BC and northwestern Washington suggest a rate of regional sea-level rise of about 1.7 ± 0.5 mm/yr, close to the global mean (Mazzotti et al., 2007).

Two long-running tide gauges in the GVRD region are located in Vancouver Harbour beside the downtown Sea Bus Terminal and at Point Atkinson at the entrance of Burrard

Inlet. The gauges have been operating continuously since the 1910s, with a gap between 1920 and 1940. Both gauge series show yearly to decadal scale signals (e.g., El Nino) similar to that at other gauges in southern BC (Fig. 14). These two criteria (record length and regional similarity) are critical in identifying good quality data for long-term sea-level rise estimates (cf., Douglas 1991). Least square fits of the monthly mean sea-level data indicate a rate of relative sea-level rise of 0.8 ± 0.2 and 0.0 ± 0.2 mm/yr for the Vancouver and Point Atkinson gauges, respectively. A more detailed analysis of these data, involving regional filtering of yearly to decadal signals, yields rates of 0.7 ± 0.1 and 0.3 ± 0.1 mm/yr, respectively (Fig. 14) (Wolynec, 2004). However, further analysis also points to significant issues in the datasets. Both tide gauges have been moved and relocated several times over their lifetime. In one case for the Point Atkinson data, the relocation was associated with an incorrect tie and an artificial offset in the series of 30-40 mm, thus biasing the rate by as much as 0.4 mm/yr. In addition, recent levelling data show instability of the pier on which the Vancouver gauge is mounted. Thus, the RSL rates derived from these two gauges are subject to significant uncertainties and should be considered with caution.

In principle, the regional sea-level rise (oceanographic component only) can be derived from a single tide gauge data set if the land vertical motion at the gauge site is known. Vertical land velocities at the Vancouver and Point Atkinson tide gauges can be estimated from the geodetic data sets presented above. InSAR and levelling only provide relative rates, with respect to some arbitrary reference, but the comparison with GPS rates suggests that the three data sets are close to an “absolute” reference (cf., Section 5). For the Vancouver site, we use the nearby BCVC GPS site (~2 km away), 14C1J levelling benchmark (~150 m away), and InSAR rates averaged over a 200-m radius circle centered on the tide gauge location. All 3 techniques indicate a vertical land velocity of ~0 mm/yr. Adding the tide gauge relative sea-level rate of 0.7 mm/yr, we estimate a regional sea-level rise of ~0.7 mm/yr (Table 5). For Point Atkinson, the 50C9500 levelling benchmark (~25 m away) and the 200-m average InSAR rates indicate a slight land uplift rate of -0.4 mm/yr (subsidence). Adding the tide gauge relative sea-level rate of 0.3 mm/yr, we estimate a regional sea-level rise of about -0.1 mm/yr (Table 5). These two estimates combined together suggest a very slow rate of regional sea-level rise of about 0.3 ± 0.8 mm/yr. The associated standard deviation takes into account the formal uncertainty on each vertical motion technique (0.1-1.2 mm/yr), on the GPS reference frame alignment (~0.5 mm/yr), and on the tide gauge data (~0.1 mm/yr). This regional rate is significantly lower than the estimate of 1.7 ± 0.5 mm/yr based on other gauges in the region (Mazzotti et al., 2007). Because of this discrepancy and the problems with the Vancouver and Point Atkinson tide gauge datasets, we use the higher regional value in calculations of relative sea-level rates.

6.2. Projected relative sea-level rise along the Fraser River delta

Relative sea-level along the Fraser River delta, and elsewhere in the GVRD, is a function of regional sea-level change and local land vertical motion. As discussed in Section 5.2, the vertical motion map derived by integration of InSAR, levelling, and GPS data gives an estimate of the vertical velocity in the ITRF2000 reference system, within an uncertainty of about 0.5 mm/yr. Thus, we can combine local vertical velocities with estimates of regional sea-level rise to estimate relative sea-level rise along the GVRD water front. Uncertainties in the projected sea-level rise over the next 100 years are described in detail in the IPCC reports and account for variations in climate and ocean models and parameters (Meehl et al., 2007). The predicted global mean sea-level rise for 2100 falls within 30-50 cm. However, this range does not account for the possibility of enhanced polar ice melting, which could lead to up to 80-90 cm sea-level rise by 2100 (Overpeck et al., 2006).

To account for the sea-level rise sources of uncertainty, we produce three scenarios for the 2100 sea level in the GVRD region. We use the IPCC range of 30-50 cm as the most likely case (Meehl et al., 2007), but we also consider a fast case at 80-90 cm (polar ice melting scenario) and a slow case at 5-10 cm. This latter scenario would assume that the low 20th century RSL rate derived from the two local tide gauges is indicative of a specific unknown process keeping the sea level around the GVRD lower than the regional average. For the land subsidence value, we extrapolate over 100 years three rates based on representative locations on the InSAR map: (a) 0-1 mm/yr for the Lulu Island delta front; (b) 1-2 mm/yr for most of the Fraser River delta; and (c) 3-4 mm/yr for the Coal Terminal (Deltaport).

The combinations of these different scenarios are presented in Table 6. Over the next 100 years, our mean estimate of relative sea-level rise for the Fraser River delta is 40-70 cm for a natural background subsidence rate of 1-2 mm/yr. Regions of the Fraser River delta affected by faster subsidence could experience relative sea-level rise as high as 110-130 cm, depending on their locations and on the actual regional sea-level increase. The two main uncertainties in these estimates are: 1) the uncertainty in the estimate of regional sea-level rise values and their projection over the next 100 years, and 2) extent to which the subsidence rates of large construction loads will diminish with time.

7. DISCUSSION

Height changes at over 60 benchmarks with respect to an assumed constant network mean from 1958/59 to 1977 show an average subsidence rate in the Holocene delta (Richmond and parts of Delta municipalities) of 1-2 mm/yr compared to uplift of 0-1 mm/yr in the Pleistocene Highlands (Vancouver, Burnaby, Surrey, Tsawwassen Heights). Comparison of the geodetic levelling results with the results from InSAR (Figure 15) shows that, to a first order, the two methods are in agreement. The broad regional pattern of 1-2 mm/yr subsidence of the Holocene delta versus 0-1 mm/yr uplift of the Highlands is clear in both data sets. Levelling and InSAR show a narrow corridor of subsidence extending eastward of Annacis Island between New Westminster and Surrey. This corresponds to a narrow tongue of Holocene sediment extending north eastward from the main delta (Figure 2). Both levelling and InSAR results exhibit a strong correlation between subsidence and presence of Holocene sediment. However, there does not seem to be any clear correlation between subsidence rate and thickness of Holocene sediment.

Large subsidence rates (> 5 mm/yr) at three levelling bench marks in southern Richmond are not confirmed by the InSAR results. This discrepancy might reflect the difference between localized levelling points versus spatially smoother InSAR estimates, or the benchmarks may be located at construction loading sites. The statistical comparison between levelling and InSAR rates discussed in Section 4.3.1 shows that the differential levelling rates are about 3 times faster than InSAR rates but with a large uncertainty. This may reflect a location bias for benchmarks, which are usually placed on road allowances, likely sites of recent construction loading. More rapid subsidence rates in some places can also be seen in the InSAR data. These locations may also be sites of construction loading. The levelling results at the BC Ferries Terminal on the Tsawwassen Causeway (Section 4.2, Figure 10) clearly show subsidence rates due to construction loading diminishing with time. A study taking into account construction dates of benchmark and buildings is required to asses the effect of construction on the overall average vertical velocities. Nevertheless, there does appear to be a background subsidence rate of about 1-2 mm/yr relative to the more stable highlands, in line with theoretical considerations.

An assessment of the flood potential of low-lying areas of the GVRD requires a knowledge of the regional rate of sea-level rise along the British Columbia coast together with an estimate of the mean vertical velocity of the mapped area in a global reference frame. If the area as a whole were uplifting, this would reduce the relative rate of sea-level rise and reduce the flood potential, and vice-versa. Because of uncertainty in the local tide gauge measurements, we have adopted a regional rate of sea-level rise derived from a joint tide gauge-GPS analysis. Figures 13 and 15 show that the vertical velocity map, derived from InSAR and checked against geodetic levelling, is consistent with vertical velocities from GPS in a global geodetic reference frame. Hence, we can estimate present-day and future relative sea-level rates at any point in the GVRD by subtracting the uplift rate for that point from sea-level rise rates under different prediction scenarios, as we demonstrate for three locations in Section 6.2 and Table 6. An uncertainty in estimating the present-day regional rate of sea-level rise comes as a result of possible unknown biases in the GPS reference frame on the order of 1 mm/yr, but this would not change the range of values expressed in Table 6 significantly.

Given the possible biases in the GPS reference frame in the vertical component, it is reasonable to ask whether the velocities in our map are reasonable from what we know about the physical processes affecting the GVRD. New postglacial rebound models for relative sea-level change over the last 10,000 years indicate low present-day uplift rates. Data from the northern Strait of Georgia show a present-day uplift rate of approximately 0.25 mm/yr (James et al., 2005). Recent modeling of the last ice sheet in southern British Columbia (Clague and James, 2002) suggests a similar uplift rate for the GVRD. The effect of Cascadia subduction fault loading on the Lower Mainland is strongly model dependent. A simple elastic model gives slow uplift of about 0.2 mm/yr with a slight east-down tilt (0.3 mm/yr between the GPS sites BCLI and BCMR (Figure 1) (Mazzotti et al., 2003; Wang et al., 2003). In contrast, some visco-elastic models give an uplift of about -0.5 mm/yr (slow subsidence) with a slight east-up tilt (0.5 mm/yr between BCLI and BCMR) (J. He, 2007, pers. comm.). On average the mapped velocities do tend to be higher in the eastern part of the GVRD but since the velocity errors also increase eastward (Figure 5), the existence of a tilt cannot be confirmed.

An observed background subsidence rate of 1-2 mm/yr in the areas of recent Holocene deposits is entirely reasonable on the grounds of deltaic sediment compaction modeling (Meckel et al., 2006, 2007). Thus, both the subsidence and the uplift rates in the vertical velocity map are physically reasonable. However, the low relative sea-level rates at Vancouver and Point Atkinson are puzzling. A possible effect on sea-level by long-term changes in Fraser River discharge should be investigated, although a preliminary analysis has shown that the Fraser River discharge does not seem to contribute to sea level variations at Friday Harbour to the south (Vanicek, 1978).

8. CONCLUSIONS AND RECOMMENDATIONS

The Holocene Fraser delta occupied by Richmond and parts of Delta municipalities is subsiding at an average rate or 1-2 mm/yr. There is no strong correlation between subsidence rate and thickness of Holocene sediment. A number of sites within the subsiding area having dimensions up to a kilometer are subsiding at a more rapid rate of 4 mm/yr or more. These are probably sites of relatively recent construction loading. The BC Ferries Terminal at Tsawwassen, for which historical levelling data are available, exhibits subsidence rates that have diminished from 15 mm/yr in the 1960's and 1970's to 3 mm/yr in the 1990's. More work is needed to determine the effect of the age of engineering structures on the observed vertical velocities. The deployment of RADAR reflectors at both sensitive installations and at sites away from construction loading is recommended. We consider local measurements of relative sea-level rise to be inconclusive and recommend estimating relative sea-level rates for sites in the GVRD by adding subsidence rates from the present map to estimates of sea-level rise based on regional and global studies.

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APPENDIX 1 – ASSESSMENT OF LEVELLING ERRORS

To evaluate the significance of the observed vertical height changes, the effect of both random and systematic errors are assessed. The combined random errors from the least-squares adjustment of the two network surveys were calculated with respect to the common network mean by geometrically adding the formal errors of the two surveys (Fig.A1). Systematic errors due to rod-scale error, atmospheric refraction and the effect of the magnetic field on automatic-level instrumentation are estimated separately. Rod-scale and refraction errors, in particular, are important to consider as they tend to correlate with topographic height which, in turn, correlates with the mechanical competence, and possibly the vertical movement, of the surface material in the Greater Vancouver area. Height corrections applied to the 1977 survey heights at bench marks common to the 1958/59 and 1977 surveys for rod scale error, refraction and magnetic effect are shown in Figures A2a, A2b, and A2c, respectively. Since rod calibrations and air temperatures are not available for the 1958/59 survey and the 1958/59 survey was not subject to magnetic effect errors, no corrections for systematic errors were applied to the results of that survey but rod-scale and refraction errors have been estimated based on the 1977 data. Magnetic effect corrections apply only to the 1977 survey when new technology (the NI1 automatic level) was introduced. It is assumed that any residual error resulting from uncorrected magnetic effects in the 1977 survey would appear as a uniform tilt across the entire region and is, therefore, not included in the total error estimates.

A1.1 Rod-scale calibration and refraction errors

Systematic errors in both the 1958/59 and 1977 surveys resulting from rod calibration errors are estimated from typical 1977 rod scale calibration errors for invar rods. It turns out that the rod-scale calibration factors applied to the 1977 heights are approximately equal to the one sigma uncertainty associated with the calibration of a single invar rod. Since matched invar rods were used in both the 1958/59 and 1977 surveys, the uncertainty in heights from rod mis-calibration in each survey is an average of the uncertainties in the two rods, or the uncertainty in a single rod divided by $\sqrt{2}$. On the other hand, the combined errors generated by differencing heights from the two surveys requires multiplication by the same $\sqrt{2}$ factor, since rod-scale uncertainties in 1958/59 and in 1977 are judged to be similar. Thus, the net uncertainty due to rod mis-calibration when expressed in terms of an apparent change in height due to topography is equal to the height corrections actually applied to the 1977 survey results (Fig. A2a). Systematic errors due to refraction in both the 1958/59 and 1977 survey are estimated from computed 1977 refraction corrections. We have used the actual refraction corrections applied to the 1977 bench mark heights (Fig. A2b) as an estimate of the one sigma errors due to refraction to be expected in the 1958/59 heights.

A1.2 Combined random and systematic errors

Since the systematic errors discussed above tend to be conserved around a given levelling loop, they will not be eliminated by the least-squares adjustment process and must be considered separately. Refraction errors may not be totally conserved around a levelling route due to temperature changes during a survey. This component of refraction error would appear as mis-closure and would be included in the network adjustment ‘random’ error budget. Thus, considering refraction error to be conserved leads to a slight overestimate of systematic error.

A combined estimate of uncertainty in height change due to rod-scale and refraction errors is made by geometrically combining the two systematic error estimates expressed with respect to the mean height of the common 1958/59 and 1977 bench marks (Fig. A3). The combined, one-sigma systematic errors in the height change from 1958/59 to 1977 for the common bench marks are generally less than 5 mm with the exception of a small area of higher elevation in Burnaby where the systematic errors reach 7 mm. An estimate of total error (random plus systematic error) in the vertical movements given in Table 3 and Figure A4 can be obtained by geometrically combining the height errors shown in Figures A1 and A3. The total errors are generally 4 mm or less, except at outlying areas of the network and areas of higher elevation where the errors reach 6 - 8 mm (Fig. A4). These errors when converted to vertical velocities result in errors in the range of 0.3 to 0.5 mm/yr (Fig. 8).