An Examination of the Factors Affecting Relative and Absolute Sea Level in Coastal British Columbia

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2008

Canadian Technical Report of Hydrography and Ocean Sciences 260

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AN EXAMINATION OF THE FACTORS AFFECTING RELATIVE AND ABSOLUTE SEA LEVEL IN COASTAL BRITISH COLUMBIA

by

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HTML version: Cat. No. Fs97-18/260E-HTML ISBN 0-711-6764
PDF version: Cat. No. Fs97-18/260E-PDF ISBN 0-711-6764

Correct citation for this publication:

Thomson, R.E., Bornhold, B.D., and Mazzotti, S. 2008. An examination of the factors affecting relative and absolute sea level in coastal British Columbia. Can. Tech. Rep. Hydrogr.Ocean Sci. 260: v + 49 p.

ABSTRACT

Thomson, R.E., Bornhold, B.D., and Mazzotti, S. 2008. An examination of the factors affecting relative and absolute sea level in coastal British Columbia. Can. Tech. Rep. Hydrogr.Ocean Sci. 260: v + 49 p.

It is now generally accepted that global climate change is occurring and that this change is responsible for the observed ongoing rise in global sea level. This report summarizes our current understanding of sea level variability in the world ocean, with particular focus on the coastal regions of British Columbia and northwestern Washington State, including estimates for future global and regional sea level rise and their uncertainties. The report further addresses the implications for extreme events, such as those due to storm surges and El Niño-Southern Oscillation (ENSO) events, and provides guidance to coastal communities and provincial authorities in planning for sea level rise. A preliminary list of research priorities needed to improve our predictions of sea level change during the 21st Century is also presented.

RÉSUMÉ

Thomson, R.E., Bornhold, B.D., and Mazzotti, S. 2008. An examination of the factors affecting relative and absolute sea level in coastal British Columbia. Can. Tech. Rep. Hydrogr.Ocean Sci. 260: v + 49 p.

Il est communément reconnu que le changement climatique global qui se produit présentement est responsable de la monté observée du niveau moyen des mers. Ce rapport résume nos connaissances actuelles de la variabilité du niveau des mers, en particulier pour les régions côtières de la Colombie Britannique et du nord-ouest de l'état de Washington, y compris une estimation des futurs niveaux marins globaux et régionaux et de leurs incertitudes. Le rapport discute subséquemment les conséquences des événements extrêmes, tels que les vagues de tempêtes et El Niño-Oscillation Australe (ENOA), et donne des indications aux communautés côtières et aux autorités provinciales pour la planification pour la monté du niveau marin. Une liste préliminaire établit les priorités de recherche nécessaires pour améliorer nos prédictions de changement du niveau marin au cours du 21eme siècle.

PREFACE

Relative sea level variability consists of highly predictable tidal fluctuations and much less predictable non-tidal fluctuations superimposed on a long-term trend. Non-tidal sea level fluctuations in British Columbia can vary regionally from time scales of a few minutes – in the case of great (magnitude ~9) earthquakes – to a few hours for storm surges, to centuries for slower tectonic uplift and subsidence. Sea level variations in coastal British Columbia are also characterized by a large seasonal cycle and marked decadal-scale variability associated with major El Niño-Southern Oscillation (ENSO) events originating in the equatorial Pacific. Relative sea level trends are primarily determined by the eustatic sea level rise due to global changes in ocean volume, local and regional vertical land movement attributable to tectonic deformation, and continued isostatic adjustment of the land following the retreat of continental ice sheets after the last ice age. Factors contributing to eustatic sea level change include the melting of ice caps, continental ice sheets and mountain glaciers, global changes in ocean water temperature and salinity (steric effects), and the variations in the storage of water in land-based reservoirs. Steric sea level change can also occur on more local scales due to regional changes in river runoff, vertical mixing and circulation.

Based on present mean rates of sea level rise and a projected 30 cm rise in mean eustatic sea level during the 21st Century, relative sea level in Vancouver, Victoria, and Prince Rupert will undergo a mean rise of 20 to 30 cm by 2100 with a range (90% confidence interval) of 10 to 50 cm due to uncertainties in oceanic and land motions.

For the Fraser River delta, relative sea level by 2100 is predicted to rise by around 50 cm with a range of 30 to 70 cm. Due to ongoing tectonic uplift, relative sea level on the west coast of Vancouver Island and western Juan de Fuca Strait will only rise about 5 to 15 cm with a range of -5 to 25 cm. More extreme estimates – based on the not unrealistic possibility that rapid ice sheet melting will cause global mean sea levels to increase by 100 cm by 2100 – leads to predicted relative sea level rise of 90 to 100 cm for Vancouver, Victoria, and Prince Rupert, 120 cm for the Fraser River delta, and 70 to 80 cm for the west coast of Vancouver Island. The uncertainties in these predictions mainly arise from uncertainties in future global and regional eustatic sea level rise. For some estimates, there is additional uncertainty associated with low accuracy in local land motion and sea level trends. Uncertainties will remain high until there are reliable GPS, satellite altimetry and tide gauge time series longer than approximately 5, 25 and 50 years, respectively.

Superimposed on the long-term sea level trend are annual cycles of 30 to 50 cm due to seasonal fluctuations in atmospheric pressure (the inverse barometer effect), regional steric effects, and wind and current velocity. Major ENSO events such as those of 1982/83, 1991/92 and 1997/98 add another 30 to 40 cm to coastal sea level. Major storm surges in low lying regions such as the Fraser River delta can add another 100 cm and typically occur in late fall to early winter when there is the possibility of high spring tides. The highest recorded sea level in British Columbia occurred on 16 December 1982 in the Fraser Delta region during a major storm at the time of a strong El Niño in the Pacific Ocean. Because this event also coincided with a high spring tide, it resulted in significant flooding in the delta region. If the frequency and magnitude of ENSO events increases with global climate change and rising global sea level, the impacts of storm surges will become increasingly more severe over the course of the 21st Century. The possibility of increased storm intensity and duration associated with global warming could also lead to higher wind waves and swell in winter which would, in turn, lead to greater land erosion and flooding during periods of high tide.

A great (magnitude ~9) Cascadia subduction earthquake has only a 5-10% probability of occurring during the next 50 years. Based on numerical models and empirical evidence from previous earthquakes, such an event would result in sudden subsidence and rapid relative sea-level rise of 30 to 200 cm on the west coast of Vancouver Island. Subsidence and relative sea-level change would diminish rapidly eastward, with predicted amplitudes of less than ~20 cm for Victoria and less than ~10 cm for Vancouver.

1.0. INTRODUCTION

Most scientists and, increasingly, most world governments generally now accept that global climate change is occurring and that this change is, in part, driven by anthropogenic greenhouse gas emissions. This consensus has led to a need to understand the consequences of climate change in order that adaptive strategies can be developed. Evidence for climate-induced sea level rise is of particular importance as it threatens large and growing coastal populations around the globe. Particularly at risk are low-lying areas in the developing world (e.g., Bangladesh) where there is insufficient internal capacity to adapt. Nations in the developed world have greater economic resources to adapt to rising sea levels through infrastructure development coupled with improved land-use planning. In all cases, it is essential to minimize risk and to optimize adaptation investments guided by the best possible estimates of future relative sea level rise.

Although it is dominated by a rocky, high-relief coast, British Columbia is not immune to the impacts of sea level rise. Two areas have been identified as being particularly vulnerable: the Fraser River delta and the east coast of Graham Island (Haida Gwaii) in the Queen Charlotte Islands. Other vulnerable areas include river deltas which would be subject to human development. The purpose of this report is to present a summary of our current understanding of sea level change for British Columbia, including present estimates for future global and regional sea level change (and their uncertainties) and the implications for extreme events such as storm surges, and to provide guidance to coastal communities and provincial authorities in planning for sea level rise. A preliminary list of research priorities to improve our predictions of sea level change during the 21st Century also emerged during formulation of this report.

This report addresses the four principal driving mechanisms effecting relative sea level variability (i.e., sea level variability measured *relative* to the land): (1) mass-induced eustatic changes in oceanic volume due to the melting of mountain glaciers, ice caps and continental ice sheets, and water impoundment in the world's artificial reservoirs; (2) expansion-induced eustatic changes in oceanic volume resulting from thermal and salinity effects on water density (steric effects); (3) regional volume changes due to dynamic atmospheric and ocean processes (including regional steric height changes associated with major rivers and local heating effects); and, (4) local geodynamic changes in relative sea levels due to vertical land motions associated with isostatic and tectonic processes. While the general nature of these factors is well-understood, the details are not. As indicated in this report, even estimates of past sea level rise for the past few decades are relatively poorly constrained. Without a much improved comprehension of the many processes and their feedbacks, predictions of future sea level change will be characterized by large uncertainty.

2.0. GLOBAL SEA LEVEL

2.1. GLOBAL EUSTATIC MEAN SEA LEVEL CHANGE

The long-term history of sea level on Earth includes widespread continental flooding such as occurred during the Cretaceous period (roughly 145 to 65 million years ago) which was followed by gradual regression of inland seas. Sea levels during the Cretaceous were 85 to 270 m higher than today (Müller et al., 2008) due to the absence of polar ice caps and major differences in the volumes of the ocean basins arising from seafloor spreading processes. Over the past few million years, changes in sea level have been largely dominated by freezing and thawing of large continental ice sheets which determined the volume of the world's oceans. In more recent times, global sea levels have changed dramatically during the late Quaternary period, rising more than 120 m over the past 18,000 years, the time of onset of rapid deglaciation following the Last Glacial Maximum around 21,000 years before present (years BP) (Figure 1). This change was most rapid between 15,000 and 7,000 years BP when sea level rose from a lowstand of about -120 m to about -3.5 m, an average rate of change of 13 to 14 mm per year. Global sea levels stabilized about 2,000 to 3,000 years BP and remained nearly constant until the late 19th Century [Intergovernmental Panel on Climate Change (IPCC), 2007] (Figure 2). These results are based largely on geological and archeological evidence, mainly dating elevations from known transitions from fresh-brackish water environments to marine on stable land masses (e.g., Australia, eastern South America, and West Africa) or on such features as Roman fish ponds and Roman-Byzantine-Crusader well data. Errors associated with these individual measurements are often between 0.5 m and several meters, related both to dating precision and the measurement of elevations.

Through most of the 20th Century, relative sea level change was primarily estimated using data from tide gauges located along continental land masses which are subject to variable amounts of vertical land movement. Since the early 1990s, measurements of sea surface elevation have also been obtained using satellite altimetry. The TOPEX/Poseidon and Jason satellites make it possible to compute absolute global mean sea level elevation relative to the earth's centre every 10 days over all – except the most northerly and southerly extremes – of the world ocean (IPCC, 2007).

Based on worldwide tide gauge records (corrected for vertical land movement), Church and White (2006) estimate that global sea levels during the 20th Century rose at a rate of about 1.7 ± 0.3 mm per year (Figure 3; Table 1). Beginning in 1993, when satellite altimetry became available, much higher global rates of rise, estimated at about 3.1 ± 0.7 mm per year (Chambers et al., 2002; Cazenave and Nerem, 2004; IPCC, 2007; Figure 4) and 3.2 ± 0.4 mm/year (Nerem, 2005; Figure 5), have been obtained from combined tide gauge and satellite altimetry records. Because these estimates are close to the performance limits of the technologies being used, it is not surprising that there exists a range of estimates in the scientific literature. Holgate (2007), for example, used tide gauge data to estimate the average rate of global sea level change in the 20th Century as 1.74 ± 0.16 mm/year (consistent with Church and White, 2006), with the period 1904-1953 experiencing a rate of 2.03 ± 0.35 mm/year and the period 1954-2003 a smaller rate of 1.45 ± 0.34 mm/year. The latter is notably different from IPCC (2007) for the corresponding period. (In this regard, we note that sea levels undergo large interannual oscillations which, coupled with the relatively short duration of the records, leads to large uncertainties in the derived trends.) Moreover, the IPCC report does not deal adequately with the storage of water behind artificial reservoirs. By taking into account the roughly 10,800 cubic kilometers of water that has been impounded on land within the world's artificial reservoirs and adding back the corresponding loss of -0.55 mm/yr that has occurred over the past half century, Chao et al. (2008) obtain an essentially constant rate of 2.46 mm/year over the past 80 years.

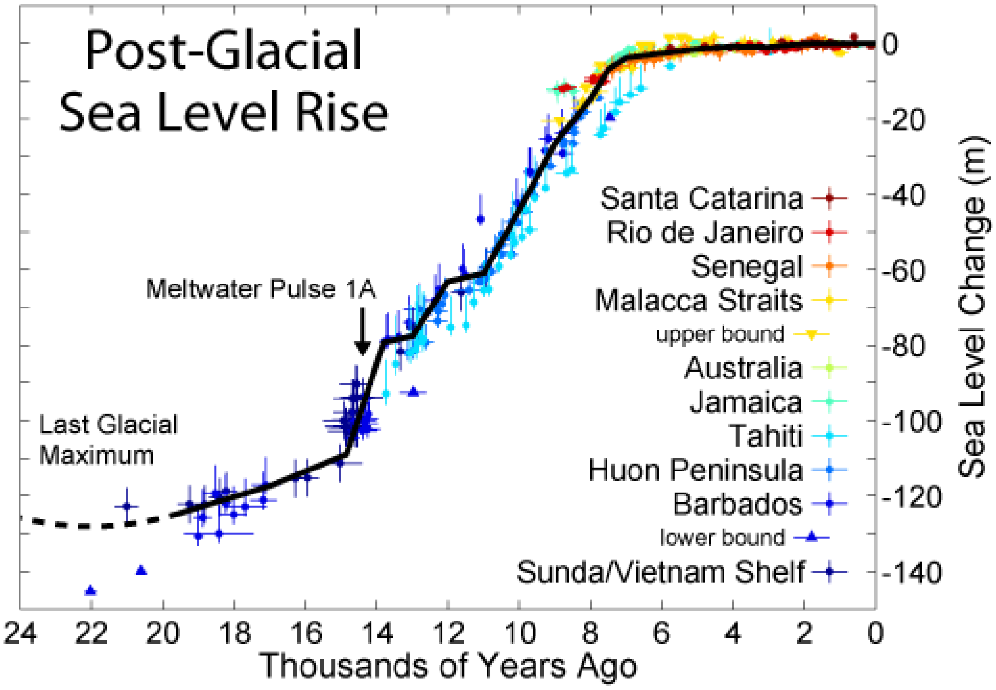

Figure 1. Global (eustatic) sea level rise since the Last Glacial Maximum (IPCC, 2007).

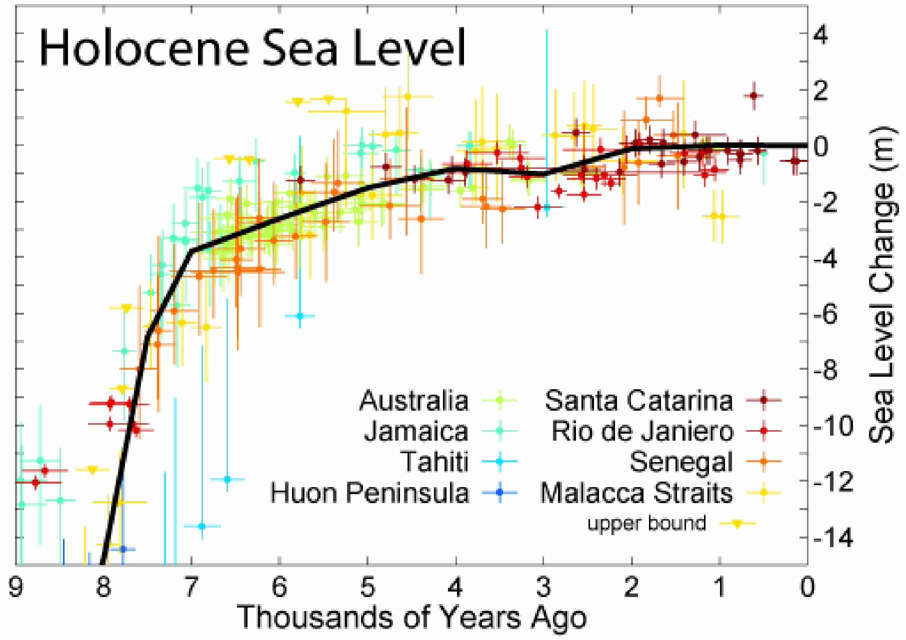

Figure 2. Holocene global (eustatic) sea level change (IPCC, 2007).

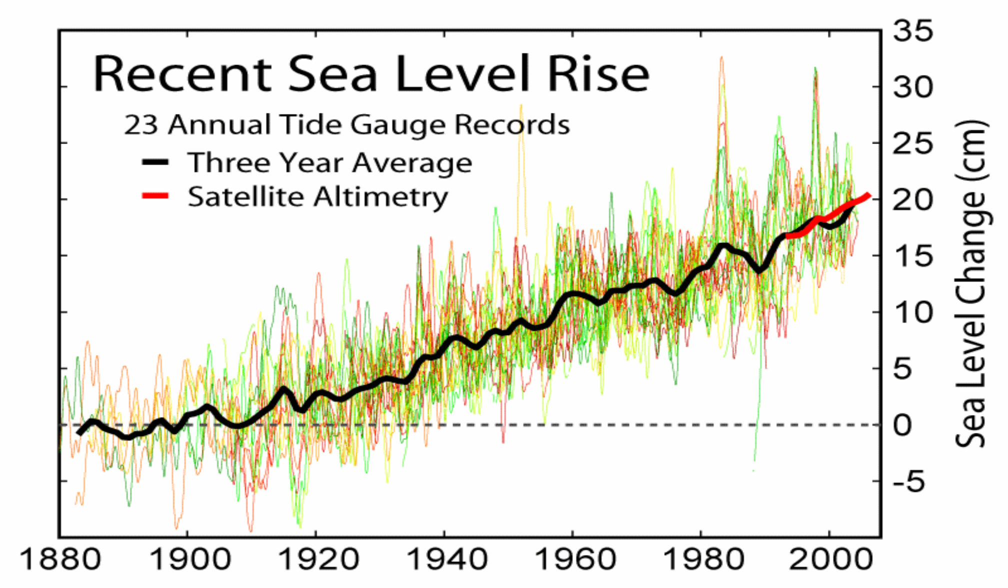

Figure 3. Recent sea level rise based on twenty-three tide gauge and satellite altimetry measurements (IPCC, 2007). The solid line is the 3-year running mean value for all data.

Source	**1961-2003**	**1993-2003**
Thermal ocean expansion	0.42 ± 0.12	1.60 ± 0.50
Glaciers and ice caps	0.50 ± 0.18	0.77 ± 0.22
Greenland ice sheet	0.05 ± 0.12	0.21 ± 0.07
Antarctic ice sheet	0.14 ± 0.41	0.21 ± 0.35
Sum	**1.10 ± 0.50**	**2.80 ± 0.70**
Observed	1.80 ± 0.50	3.10 ± 0.70
Difference (observed - sum)	0.70 ± 0.70	0.30 ± 1.00
Reservoir impoundment	-0.55	-0.55

Table 1. Annual rates of mean global sea level rise (mm/year) adapted from IPCC (2007) and Chao et al. (2008) water impoundment estimates. Note that for both time periods considered in the IPCC report, the rates of sea level rise estimated from the sum of all known process are *less than* the observed rates, although both values are consistent within their uncertainties. The recent reservoir effect proposed by Chao et al. (2008) enhances this difference.

A significant complicating factor in many areas is glacial isostatic adjustment (GIA), the continuing rebound of the solid Earth since the Last Glacial Maximum (or collapse in the case of glacial forebulges) related to the disappearance of continental glaciers. Not only does this affect the vertical elevation of the land surface, and the vertical positions of tide gauges, but it also has an impact on the global ocean basin volume. Since this effect varies around the world due to different glacial histories and rheological variations in the Earth structure, it is difficult to determine its global contribution to observed sea level change and has been the subject of a considerable scientific literature (e.g., Mitchum, 2000; Peltier, 2001; Douglas and Peltier, 2002). Satellite altimetry measurements have yielded estimates of the global ocean basin volume effect from GIA on mean sea level as -0.3 mm/year with a possible uncertainty of 0.15 mm/year (Peltier, 2001; IPCC, 2007). This rate is subtracted from altimetry-derived global mean sea level estimates in order to obtain the contribution from ocean water volume change.

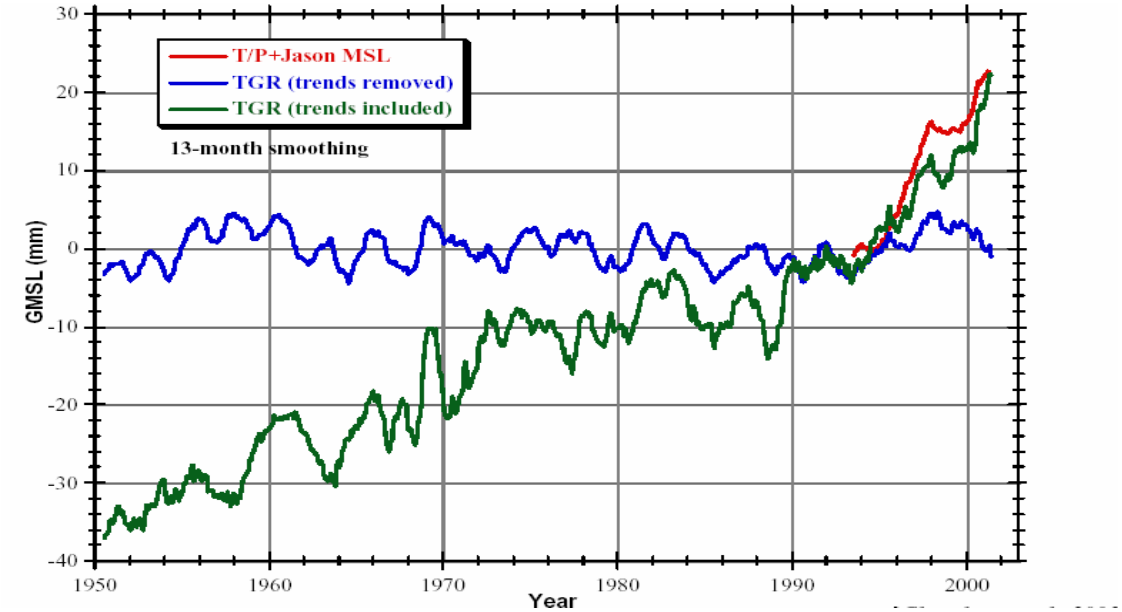

Figure 4. Global mean sea level change since 1950, based on tide gauge records (TGR, green line) and satellite altimetry (T/P, red line), showing an apparent acceleration in sea level rise since about 1993 (after Chambers et al., 2002; Cazenave and Nerem, 2003). The blue line is the trend-removed version of the tide gauge record and indicates the level of background sea level variability independent of the long-term trend.

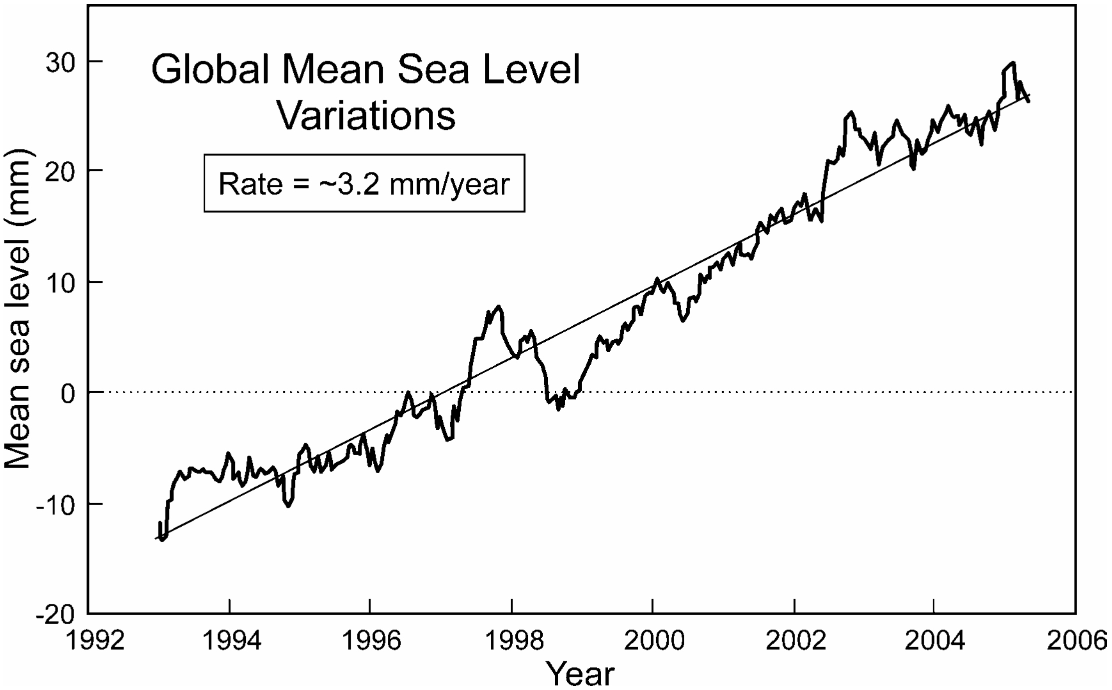

Figure 5. Change in mean sea level between 1993 and 2005 from satellite altimetry including corrections for Glacial Isostatic Adjustment (GIA) and seasonal variations (after Nerem, 2005).

Accelerated melting of the cryosphere, particularly continental ice sheets, contributes substantially to rising sea levels, although as Vaughn and Arthern (2007) point out, it is often difficult from a glaciological perspective to predict the future behaviour of ice sheets. Recent evidence has shown that, since 2002, melting of Antarctic and Greenland ice sheets has had a much greater effect on sea level rise than in the previous 20th Century (cf., Velicogna and Wahr, 2006; Zwally et al., 2006; Thomas et al., 2006; Murray, 2006). Velicogna and Wahr (2006) analyzed melting of the Greenland glaciers over the period 2002-2006 and detected a much more rapid loss of ice than previous estimates, especially near the coast and in southern Greenland. The authors conclude that for this period (2002-2006) Greenland lost about 248 ± 36 km^3, equivalent to 0.5 ± 0.1 mm/year in sea level rise, *more than twice* the rate of 0.21 ± 0.07 mm/year estimated by IPCC (2007) for the period 1993-2003 and substantially greater than the rate of 0.35 mm/year for the global mean annual ice sheet contribution presented by Shepherd and Wingham (2007) for the period 1992-2006 (see below). Velicogna and Wahr (2006) conclude that Greenland glaciers respond much more rapidly to changes in climate than was previously thought. Shepherd and Wingham (2007) summarized eleven studies of glacier mass balance that showed annual rates of loss ranging from -11 to 227 Gt (gigatonnes = 10^9 tonnes), equivalent to -0.03 and +0.64 mm sea level changes, respectively. They further state that measurements suggest a net loss of 100 Gt/year (360 gigatonne of ice is equivalent to 1 mm of eustatic sea level rise).

Many researchers over the past decade have documented the increasingly rapid disintegration of Antarctic ice shelves (e.g., Rignot and Thomas, 2002; Zwally et al., 2005; Shepherd and Wingham, 2007; Vaughn and Arthern, 2007). Although their melting does not directly contribute to a change in sea level, ice shelves provide a buttress against Antarctic glaciers and that their disintegration could lead to more rapid rates of glacial advance. While snow precipitation at higher altitudes is predicted to increase under climate warming scenarios, most mass balance estimates show there have been substantial losses in Antarctic ice sheets, particularly the West Antarctic ice sheet (summarized by Shepherd and Wingham, 2007). They find that for the period 1992 to 2006 the West Antarctic ice sheet (based on five sets of estimates) has lost between 47 and 136 gigatonnes of ice per year. All five estimates show losses compared to East Antarctic ice sheet measurements where most studies show accumulation of ice mass over the same period, but at a very much slower rates (-1 to 67 Gt per year). In a counter argument for the apparent increased rate of ice shelf collapse, Alley et al. (2007) suggest that, for the expected rates and total amounts of sea level rise over the next century, sedimentation beneath the ice shelves will act to stabilize the shelves.

Newton (2008) summarized recent studies of Antarctic ice loss noting that there has been a 75 % increase in ice discharge into the ocean over the past decade. Ice loss is believed to be caused, at least in part, by warming of waters around Antarctica, possibly due to southward migration of the Antarctic Circumpolar Current over the past several decades. Heat advected southward by the current has helped destabilization of the ice shelves.

In addition to the uncertainty associated with melting of continental ice sheets, debate continues regarding estimates of mountain glacier and ice cap melting (excluding the Greenland and Antarctic ice sheets) and their contribution to sea level rise. The IPCC (2007) report estimates sea level rise from glaciers and ice caps of 0.77 ± 0.22 mm/year for the “present” period 1993-2003 and 0.50 ± 0.18 mm/year for earlier period 1950-1993. Other authors (e.g., Raper and Braithwaite, 2006) project a lower rate of about 0.48 mm/year for the 21st Century based on estimates of sea level rise of between 0.046 and 0.051 m by 2100. Meier et al. (2007), on the other hand, project a total sea level rise of 1.0 to 2.5 m during the 21st Century from glaciers and ice caps (*excluding* Greenland and Antarctica), which is considerably higher than other projections. Arendt et al. (2002) analyzed the contributions from Alaska, Yukon and Northwestern British Columbia glaciers to sea level rise over the periods mid-1950s to mid-1990s and mid-1990s to 2000/2001; they show that over the four earlier decades, glaciers in these areas lost 52 ±15 km^3/year (water equivalent) compared to 96 ± 35 km^3/year in the last part of the 1990s, or *nearly twice the previous annual rate*. These two rates equate to a 6 to 12 % contribution to global sea level rise.

On March 16, 2008 the U.N. Environment Programme (UNEP) released its study of mountain glacier losses in 2006, comparing them with those of the previous decade (UNEP, 2008). In 2006, glaciers shrank by 1.4 m (water equivalent) in terms of ice thickness compared to half that amount in 1998. (On average 1 m water equivalent corresponds to 1.1 m of ice thickness.) The UNEP report states: "This continues the trend in accelerated ice loss during the past two and a half decades and brings the total loss since 1980 to more than 10.5 m of water equivalent … During 1980-1999, average loss rates had been 0.3 meters per year. Since the turn of the millennium, this rate had increased to about half a meter per year". "The latest figures are part of what appears to be an accelerating trend with no apparent end in sight".

The overall long-term implications of continental ice sheet, mountain glacier, and ice cap melting continue to be debated. For example, the IPCC (2007) report concludes that, because of projected increasing snow precipitation on Antarctica, the contribution of that continent to global sea level rise will not be particularly significant during the 21st Century. Moreover, they deduce that the recent accelerated sea level rise from glacial melting lies within the expected range of long-term rates. In contrast, Shepherd and Wingham (2007) state that although there has been an increase in rates of snowfall on Antarctica and on Greenland, on balance, ice sheets are losing mass at a significant rate; they conclude that the East Antarctic ice sheet is gaining mass at about 25 Gt/year, while the West Antarctic ice sheet and Greenland ice sheets are losing mass at about 50 and 100 Gt/year, respectively, providing a sea level rise contribution of about 0.35 mm/year (compared to the IPCC 1961-2003 estimate of 0.19 mm/year; cf., Table 1). While Shepherd and Wingham (2007) point out that their estimate is "a modest component of the present rate of sea-level rise of about 3.0 mm year^{-1}", they also stress that the causes of ice sheet instability are very poorly understood and that reliable predictions of future rates are impossible to make. The authors acknowledge the possibility that this rate could very well increase. Indeed, Velicogna and Wahr (2006) show that between 2002 and 2006, the southern Greenland Ice sheet alone lost ice at a rate equivalent to a global sea level rise of 0.5 ± 0.1 mm/year. In a recent publication (Monaghan et al., 2008), compare observations of near-surface air temperature and snowfall accumulation for the 20th Century with simulations from IPCC (2007) global climate models. They conclude that if Antarctic temperatures rise as projected, snowfall increases may partially offset ice sheet mass loss by canceling 1 mm/year of global sea level rise or roughly 10 cm by 2100. On the other hand, 20th century (1880–1999) annual Antarctic near-surface air temperature trends based on numerical models are about 2.5 to 5 times larger than observed, possibly due to the radiative impact of unrealistic increases in water vapor. Because estimates of snowfall rate are closely tied to air temperature and, ultimately, to ice sheet mass loss, it is important to get this aspect of the problem right. "Resolving the relative contributions of dynamic and radiative forcing on Antarctic temperature variability in the models will lead to more robust 21st century projections."

Although the IPCC (2007) report does present a scenario – termed "scaled-up ice sheet dynamical imbalance"— which projects an increasing rate of melting, these rates are substantially less than actual 1993-2003 observations. Furthermore, in its summary for policy makers, the IPCC does not address the possibility of continued rapid melting of continental glaciers or the impact of further slowdown in the construction of land-based reservoirs. Several authors have questioned the IPCC (2007) conclusion that changes in oceanic mass (addition of water from continental ice sheets and glaciers) was much less important than thermal contributions to sea level rise during the 20th Century (e.g., Miller and Douglas, 2004; Nerem, 2005). Nerem (2005) concludes that "The 'enigma' [Munk, 2002] of 20th sea level change [i.e., the discrepancy between observed and modeled sea level rise] has largely been resolved and a larger contribution from melting ice is now allowed (~ 1 mm/year)". Nevertheless, the absence of a clear understanding of the long-term trends in glacial melt-out remains one of the most serious barriers to defining precise global sea level trends (Oppenheimer, 2004), although most authors have recently concluded that the IPCC (2007) estimates for Antarctic and Greenland ice sheet contributions are unrealistically low. The IPCC (2007) readily admits to significant uncertainties in this respect: "Future changes in the Greenland and Antarctic ice sheet mass, particularly due to changes in ice flow, are a major source of uncertainty that could increase sea level rise projections. The uncertainty in the penetration of the heat into the oceans also contributes to the future sea level rise uncertainty." Chao et al. (2008) note the possibility of an accelerated rise in global sea level associated with a slowdown (or reduction) in the number of reservoirs on rivers in the near future.

2.2. REGIONAL SEA LEVEL CHANGE

Sea level observations generally exhibit considerable regional variability due to a number of regional factors, including geodynamic processes, steric effects, and changes in ocean and atmospheric circulation. The later includes variations in oceanic circulation, atmospheric pressure, and wind velocity. These factors are reviewed in this section and their contributions to anticipated British Columbia sea level changes during the 21st Century summarized in Section 3. Estimates for each major factor for the 21st Century are provided in Appendix A.

2.2.1. Steric Sea Level

As discussed in previous sections, the addition of water to the world's oceans from land-based sources (primarily continental ice sheets and glaciers) has an obvious and well publicized effect on sea levels. The contribution from the thermal expansion of marine waters is less well known although it is estimated to contribute nearly half the observed rise in mean eustatic sea level (IPCC, 2007). During the past half century, the oceans have absorbed roughly half the heating of the climate system attributable to increased emissions of greenhouse gases. These effects are neither spatially nor temporally uniform. On a broad scale, according to the IPCC (2007): "In the North Atlantic, the warming is penetrating deeper than in the Pacific, Indian and Southern Oceans. … The transfer of heat into the ocean … leads to sea level rise through thermal expansion, and the geographical pattern of sea level change since 1955 is largely consistent with thermal expansion and with the change in heat content …" (IPCC, 2007, p. 420). Due to the slow overturn of the global ocean, thermal expansion of the ocean is expected to continue for about 1,000 years after atmospheric temperatures have stabilized.

At smaller geographical scales, certain regions of the global ocean witness different degrees of thermal variability, and hence sea level change, than others. Thus, for example, the eastern and western boundary regions of the Pacific Ocean regions are strongly affected by thermal variability related to El Niño-Southern Oscillation (ENSO), manifested in part by sea level changes higher than in many other parts of the global ocean. There has been relatively little discussion on the effect that changes in ocean precipitation, coastal runoff, and vertical mixing will have on the salinity, and hence sea level, of the world ocean basins. In a study of the observed steric sea level changes in the northeast Pacific based on time series of deep (1000 m) water column temperature and salinity measurements from 1956 to 1986, Thomson and Tabata (1987, 1989) found that 67% of the estimated total 1.1 mm/year rise in steric height was due to thermosteric effects below 100 m depth whereas 33% was due to changes in the salt content above this depth. This estimate is presently being updated using all available CTD (conductivity-temperature-depth) measurements at Ocean Station "P" collected from Canadian research vessel surveys from 1986 to present (Thomson et al., in preparation).

2.2.2. Oceanic Circulation

Changes in coastal and offshore ocean circulation can have an important effect on sea level variability and long-term trend. Wind stress, which is the primary driving mechanism for currents in the upper ocean to depths of around 1000 m, effects dynamical changes in the sea surface slope and, through lateral advection, the thermal and salinity structure of the upper ocean. Both effects bring about changes in sea level. For example, decadal patterns of sea levels in the tropical Pacific Ocean show a strong correlation with the depth of the tropical thermocline and changes in the trade winds (Carton et al., 2005; Kohl et al, 2007). Because of geostrophy (current velocity is normal to the sea surface height gradient), changes in the position and velocity of currents in major ocean gyres can lead to significant regional-scale changes in sea level with a doubling of the current velocity leading to a doubling of the sea level displacement. For a typical continental shelf width of 10 km off the coast of British Columbia, a 10 cm/s increase (or decrease) in the poleward alongshore current results in a 1 cm rise (or fall) in coastal sea level. Changes in circulation affect the distributions of temperature and salinity and, therefore, the contributions from steric effects. Again, considerable uncertainty exists when attempting to predict oceanographic changes (IPCC, 2007): "Large scale ocean circulation changes beyond the 21st

Century cannot be reliably assessed because of uncertainties in the meltwater supply from Greenland ice sheet and model response to the warming."

2.2.3. Atmospheric Pressure and Wind Velocity

Sea levels regionally are directly affected by changes in surface atmospheric pressure whereby an increase in pressure depresses the sea surface, displacing water laterally to other areas (and vice versa). This "inverse barometer effect" (whereby a 1 mb pressure increase gives rise to a 1 cm fall in sea level) can effect a longer term average (e.g., seasonal) departure from local mean sea level of about 10 to 20 cm (Thomson and Crawford, 1997; IPCC, 2007).

On time scales less than a few days, sustained winds, and associated decrease in atmospheric pressure, can lead to storm surges which raise water levels by a meter or more above predicted tidal levels. Storm surges can be especially devastating in low-lying coastal areas such as Bangladesh and the Florida coast but are also of major importance in the Fraser River delta region of metropolitan Vancouver, particularly Boundary Bay which is exposed to southeasterly storm winds (Abeysirigunawardena, 2007; Tinis, 2008).

2.2.4. Geodynamics

As discussed in Section 2.1, glacial isostatic adjustment (GIA) continues in some regions of the world, leading to global changes in absolute mean sea levels as well as marked differences in relative sea levels in areas that are in close proximity. In some parts of the world, such as Scandinavia and the Arctic, GIA effects on relative sea level are still quite significant (Gornitz, 1993; Stewart et al., 1998) with extreme relative sea level fall values of up to 10 mm/year.

As meltwater flows back into the oceans from melting glaciers, it progressively loads continental margins, resulting in minor subsidence while leading to corresponding minor upward bulging of the continents. GIA also contributes to more subtle effects in terms of the Earth's rotation, as mass is redistributed, which "feeds back into the variations in the position of the crust and geoid …" (IPCC, 2007). In particular, the secular change in the Earth's dynamic oblateness (J_2) – which is related to Earth's equatorial bulge arising from rotation about its polar axis – observed during the 25 years prior to 1998 can be partly attributed to this postglacial isostatic rebound. The sudden increase in oblateness that occurred around 1998, and which would amount to a sudden additional global eustatic rise of 1.4 mm/year if it were due to mass influx, overshadowed the GIA effect and signifies a huge unexplained change in global mass distribution (possibly associated with oceanic mass redistribution rather than mass influx during the 1997/98 ENSO event) that has not been observed in modern times (Cox and Chao, 2002). Beginning in 2001, the oblateness time series appears to have returned to its pre-1998 trend. The shift in crustal mass associated with the magnitude 9.3 Indonesian earthquake on December 26, 2004 also affected the rotation speed of the earth.

Relative sea level can also change due to geodynamic processes on shorter time scales ranging from seconds to minutes, in the case of earthquakes, or years to decades under conditions of slow crustal deformation. Typical amplitudes for fault movements can range from a few centimeters to a few meters in a single event, though a series of sequential movements on a single fault are not uncommon. Crustal deformation, such as that presently occurring on Vancouver Island, can be at rates of up to a few millimeters per year (see Section 3). Often there is a combination of slow deformation culminating in a rapid release of strain through fault rupture. A prime example is that of the Cascadia subduction zone which undergoes deformation over a period of 500-600 years, on average, with a sudden release of accumulated strain in a great (magnitude ~9) earthquake (Atwater, 1987; Adams, 1990). Rapid changes in water level over periods of minutes to hours associated with these events (i.e., tsunamis) can reach maximum heights of ~10 meters at certain locations on the west coast of Vancouver Island and about 1 m in more protected waters such as the Strait of Georgia (Cherniawsky et al., 2007).

Significant subsidence is occurring on many of the world's deltas as a result of sediment loading and slow compaction. These effects are essentially local in extent and can frequently surpass more regional geodynamic or global sea level trends. Although continuous addition of sediment from the river would compensate for compaction at depth and for lithospheric loading under natural condition, human activities often lead to a diversion of new sediment away from the delta or entrapment behind dams in the river’s watershed. As a result, the delta continues to slowly subside but with no compensatory addition of new sediment. The best known example is the Mississippi Delta and the effects of this continued subsidence on New Orleans, much of which now lies below sea level. Dixon et al. (2006) calculate mean rates of subsidence at about 6 mm per year for the Mississippi Delta. There have, however, been other wide ranging estimates of subsidence rates for New Orleans, with values as high as 29 mm/ year. As we discuss in Section 3.3.1, the Fraser Delta is also subsiding at several millimeters per year, leading to rising relative sea levels in some regions of the delta. This is because, as a result of urbanization and management of the river, sediments are no longer being added to the surface of the delta platform. At localities around the world, other human activities, such as withdrawal of groundwater from aquifers beneath Venice (Zanda, 1991) or oil and gas extraction at Long Beach, California (Galloway et al., 1999) have led to additional rates of local subsidence.

3.0. SEA LEVEL OBSERVATIONS FOR BRITISH COLUMBIA

Post-glacial relative sea levels have both fallen and risen along the British Columbia coast in response to global eustatic sea level rise and to regional effects associated with local tectonics, the disappearance of glaciers, unloading of the lithosphere, and to the collapse of associated forebulges in unglaciated or less glaciated regions (e.g., Clague et al., 1982). Thus, areas near the heads of many mainland fjords in British Columbia have witnessed as much as 200 m of relative sea level fall since about 15,000 years ago due to retreat of the continental ice sheets, despite a global eustatic sea level rise of 120 m. In marked contrast, sea levels on the Queen Charlotte Islands during the Holocene have risen more than 150 m as the glacial forebulge collapsed and eustatic sea levels rose (Clague et al., 1982). This section examines the regional changes in sea level along the British Columbia coast as a result of eustatic, isostatic, tectonic and oceanographic influences, with an emphasis on the 20th Century.

3.1. ISOSTATIC EFFECTS

Most large postglacial changes in British Columbia occurred between about 15,000 and 8000 years ago, with much smaller relative sea-level changes post 8000 years (Figure 6). As noted above, however, the relative sea level histories of nearby coastal regions can be quite different. For example, the sea level history of Prince Rupert during the Holocene has been completely the opposite to that of the Queen Charlotte Islands even though they are separated by only about 100 km (Clague et al., 1982; McLaren, 2008). This difference arises from the pairing of subsidence, resulting from glacial ice loading on the continent, with the compensating uplift of a forebulge in adjacent unglaciated or less glaciated areas

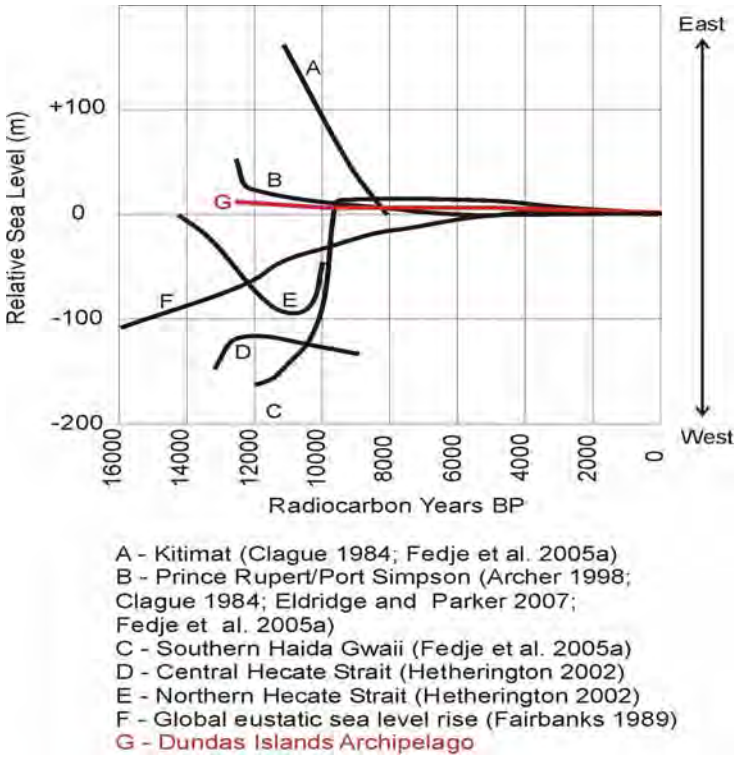

Figure 6. Relative sea level curves for northern British Columbia since deglaciation showing the wide range of sea level histories for the region (after McLaren, 2008).

This rapid response following the retreat of the ice sheet is explained by the particularly weak (low viscosity) mantle that underlies most of British Columbia (e.g., Hyndman et al., 2005). The time scale of postglacial rebound is primarily controlled by the viscosity of the upper and lower mantle in the region affected by the loading and unloading processes. In contrast to the high viscosity and long time-scale response of the Canadian Shield, British Columbia is characterized by low mantle viscosities and fast time-scale response to glacial retreat (James et al., 2000; Clague and James, 2002).

Because of the low mantle viscosity and fast response, present-day vertical velocities due to postglacial rebound are very small in most of British Columbia. Most studies and models have focused on south-western British Columbia, where present-day uplift rates are expected to be less than 0.5 mm/yr (Figure 7) (Clague and James, 2002; James et al., 2005; Gowan, 2007). Most of British Columbia is associated with a high temperature, low viscosity mantle (Hyndman et al., 2005). Thus, postglacial rebound velocities are likely very small (less than 0.5 mm/yr) for the entire coast of British Columbia.

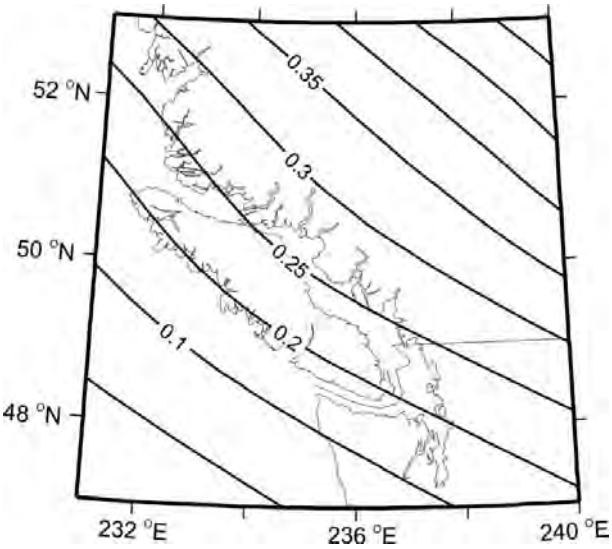

Figure 7. Predicted vertical velocities in SW British Columbia due to postglacial rebound (contours in mm/yr). Modified after Clague and James (2002) and James et al. (2005)

3.2. TECTONIC EFFECTS

Western British Columbia lies along a system of plate boundary zones between the continental North America plate to the east and the oceanic Pacific and Juan de Fuca plates to the west (Figure 8). South of ~50 °N, Vancouver Island and south-western British Columbia are affected by the ongoing subduction of the Juan de Fuca plate (and smaller Explorer plate), which is converging to the NW at about 40-50 mm/yr with respect to the North America plate. North of about 52 °N, the Queen Charlotte Islands lie along the Queen Charlotte Fault, which accommodates about 50 mm/yr of right-lateral strike-slip motion between the Pacific and North America plates. The region between these two systems (50-52 °N, northern end of Vancouver Island) is a complete triple-junction area where the three major plates interact.

The Cascadia subduction zone extends roughly from northern Vancouver Island to northern California. The subduction fault is the locus for great (magnitude ~9) subduction earthquakes that rupture every 500-600 years (Atwater, 1988; Adams, 1990). The last great earthquake occurred on January 26, 1700 (Satake et al., 1996). During this event, the west coast of Vancouver Island suddenly subsided by about 50 cm. The maximum co-seismic subsidence measured during the 1700 earthquake was about 2m, along the central Washington coast (Leonard et al., 2004). Thus, sudden subsidence and accompanying relative sea-level rise of 0.5 to 2 m can be expected along the west coast of Vancouver Island during the next great earthquake. Co-seismic subsidence and relative sea-level rise are expected to decrease significantly to the east, with maximum amplitudes of about 20 cm or less in the Victoria area. Based on information from paleo-earthquakes, Mazzotti and Adams (2005) estimate a probability of 5-10% that a magnitude ~9 great subduction earthquake will occur during the next 50 years.

The Cascadia subduction fault is currently locked and accumulates strain that will be released during the next great earthquake (Dragert et al., 1994; Mazzotti et al., 2003). The strain accumulation along the fault produces significant elastic shortening and uplift of the forearc region (west of the Cascade volcanic arc). As a result, most of Vancouver Island is predicted to experience uplift rates between 0 and 3 mm/yr. Various subduction zone models predict uplift patterns and amplitudes that can differ by as much as 2 mm/yr (Mazzotti et al., 2003; K. Wang, pers. comm., 2007). Present-day vertical motions can be measured using high-precision GPS stations with an accuracy of about 1 mm/yr. A first-order west-side-up tilt is apparent across southern Vancouver Island-Lower Mainland, where GPS sites on the west coast of the island are rising at 2 to 3 mm/yr, whereas sites around Vancouver show near-zero velocities (Figure 9). However, the details of the vertical velocity pattern are more complex than expected from subduction models alone. For example, the fast uplift rates on northern Vancouver Island cannot be only related to the ongoing Juan de Fuca and Explorer subduction system. Further discussion of vertical land motion arising from Cascadia tectonics is found in Mazzotti et al. (2007), Lambert et al. (2008), and Mazzotti et al. (2008a,b).

North of approximately 51 °N, the tectonics are dominated by the strike-slip relative motion between the Pacific and North America plates. Although most of the tectonic deformation is accommodated along the Queen Charlotte fault offshore, recent studies suggest that a small fraction (~10%) of the relative motion may be distributed across the margin as far inland as the Coast Mountains (Mazzotti et al., 2003b). Although such a strike-slip system is not expected to produce significant vertical land motion, uplift rates of about 2-3 mm/yr are observed at all GPS stations, except Prince Rupert, along the north-central coast and the southern Alaska Panhandle (Figure 9). GPS data at the Prince Rupert station are short and the measured subsidence may be an artifact of the limited dataset.

The GPS data clearly indicate that most of the BC coast is affected by vertical land motion as large as 1 to 3 mm/yr. These velocities are of the same order of magnitude as the rate of eustatic sea level rise and thus can significantly increase or decrease the local relative sea level changes. The impact of vertical land motion can also vary over relatively short distances, with sites rising at 2 mm/yr within a few 10s of kilometres of sites that show no vertical motion.

It is important to note that there are significant uncertainties associated with measuring vertical land motion. In particular, most techniques (GPS, traditional levelling, tide gauges) are susceptible to systematic biases and random noise (cf. Mazzotti et al., 2007). For example, the levelling and GPS results quoted in Mote et al. (2008) suggest large uplift rates (2-3 mm/yr) in the Vancouver area, in contrast with our results that show zero vertical motion (Fig. 9). This discrepancy is explained partly by the lack of Canadian data included in the studies reference in Mote et al. (2008) and partly by the difference techniques used to align the vertical land motion to an absolute reference (mean water level).

Although the main processes affecting vertical land motion in British Columbia are relatively well understood (postglacial rebound, subduction, and strike-slip plate boundaries), the details of the vertical land motion measured by GPS cannot be fully explained by the existing postglacial rebound and tectonic models. Empirical (GPS and tide gauge-based) measurements of vertical land motion remain the most robust tools to estimates total uplift and subsidence over the next decades to century time scales.

Figure 8. Topography and current tectonics of British Columbia. The primary plate boundary faults off the west coast are the Cascadia Subduction Zone (CSZ) and the Queen Charlotte Fault (QCF). Jdf denotes the Juan de Fuca plate.

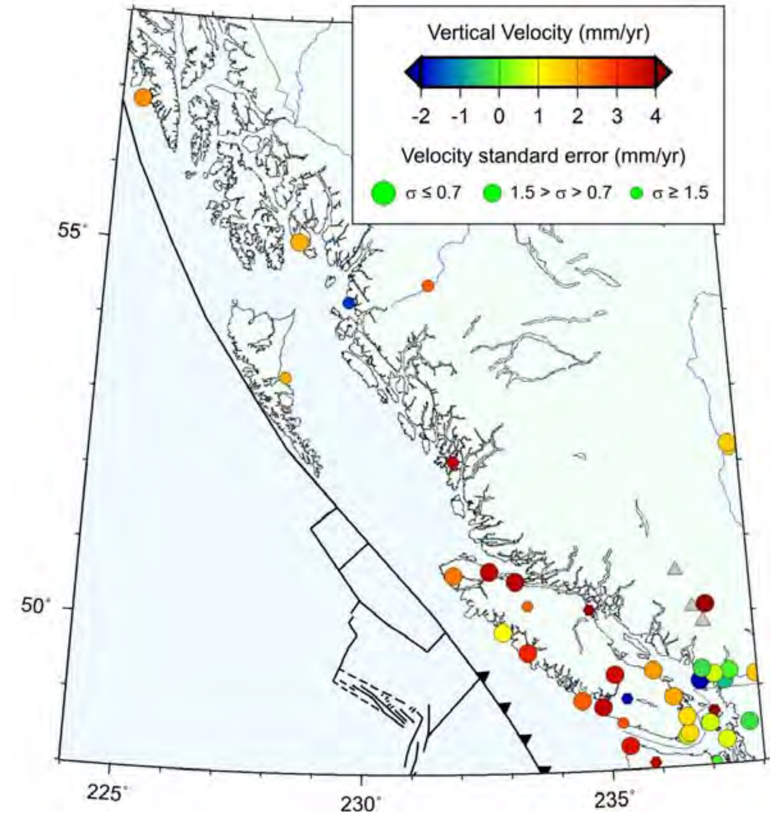

Figure 9. Vertical land movement at GPS stations in British Columbia. The locations are permanent GPS stations operated by the Geological Survey of Canada and the British Columbia Base Mapping and Geodetic Services. Velocities are aligned to a global reference frame and mean sea level (modified after Mazzotti et al., 2008b).

3.3. SEDIMENTARY EFFECTS/FRASER DELTA SUBSIDENCE

Recent investigations (Lambert et al., 2008; Mazzotti et al., 2008a) have quantitatively analyzed changes in the elevations across and adjacent to the Fraser Delta during the latter half of the 20th Century (Figure 10). Results in Lambert et al. (2008) were based on: (1) a re-analysis of first-order geodetic leveling carried out in 1958-59 and 1977 for 61 benchmarks; (2) satellite-based Coherent Target Monitoring Interferometric Synthetic Aperture RADAR (CTM-InSAR) using 30,000 ground targets; and (3) continuous Global Positioning System (GPS) data at 5 permanent sites across the greater Vancouver region. Standard error on individual leveling, InSAR, and GPS vertical velocities are on the order of 0.1 to 1.5 mm/yr, with the primary source of uncertainty being the alignment of inherently relative velocities (leveling and InSAR) to a global reference frame and to the regional mean sea level (using GPS data). For example, standard errors associated with the CTM-InSAR data range between 0.2 and 0.4 mm/year for the western part of the Fraser Delta area to 0.6 to 0.8 mm/year, typically, for the eastern part of the study area. The integration of two or three data types in many areas enabled the authors to achieve further confidence in the measured rates.

The results of Mazzotti et al. (2008a) show an average subsidence rate for the Holocene delta (Richmond and Delta municipalities) of 1-2 mm/year, compared to negligible uplift of adjacent Pleistocene upland areas (Vancouver, Surrey, Burnaby, Tsawwassen Heights) of 0-0.5 mm/year (Mazzotti et al., 2008a; Figure 10). Earlier estimates of average annual Fraser Delta subsidence, based on geodetic leveling, for the period 1919-1958, were 3.51 mm/year (Mathews and Shepard, 1962). While there is a clear association between Holocene sedimentation and subsidence in general, Lambert et al. (2008) found no apparent direct relationship between known sediment thicknesses (up to 300 m) and rates of subsidence. A more detailed analysis suggests that most of the ongoing sediment compaction (and related subsidence) is limited to the first 10-20 m of the Holocene sediments, commonly comprising silt and peat sediments (Mazzotti et al., 2008a).

Higher subsidence rates (> 3 mm/year) are mostly related to large construction projects such as the British Columbia Ferry Terminals (BC Ferries Tsawwassen Terminal) and port facilities (Deltaport) or the Vancouver International Airport. These elevated rates diminish with time following construction following a first-order exponential curve with a time constant of ~20 years (Mazzotti et al., 2008a). As an example, the authors show that the BC Ferries Terminal at Tsawwassen experienced approximately 15 mm/year subsidence in the 1960s and 1970s but that these rates had diminished to about 3 mm/year by the 1990s (Figure 10 in Lambert et al., 2008). In most cases, high subsidence rates most likely result from rapid and greater compaction of underlying sediments due to the additional high load of new construction.

A detailed examination of the 45-year tide gauge record for Point Atkinson in West Vancouver from 1963 to 2007 (A. Rabinovich, pers. com, 2008), including “corrections” for the data gaps of several months in 1978, 1983 and 1997, reveals the absence of a long-term trend, in agreement with Mazzotti et al. (2008b). This site is located on solid rock and is thought to represent a stable platform for estimating the effects of eustatic (global) sea level rise on the Vancouver region. If we make the logical assumption that the Strait of Georgia is affected by the global mean rise of roughly 1.7 mm/year, the Point Atkinson tidal height analysis suggests that the land site has been rising from GIA or tectonic processes at a minimum rate of 1.7 mm/year for the past 45 years. If we also take into account the roughly 0.8 mm/year relative sea level rise due to the halosteric effect observed at the Nanoose Bay test range site from 1979 to 2007, then the Point Atkinson gauge land site has been rising vertically at a rate of nearly 3 mm/year over the past 30 years. This is a surprising result. When combined with the observation that the Vancouver and Cherry Point tide gauge records also lack significant long-term trends and the fact that there is no significant uplift in the bedrock around Vancouver (Mazzotti et al., 2008), the Point Atkinson finding is clearly problematic and points to a need for additional measurement and analysis.

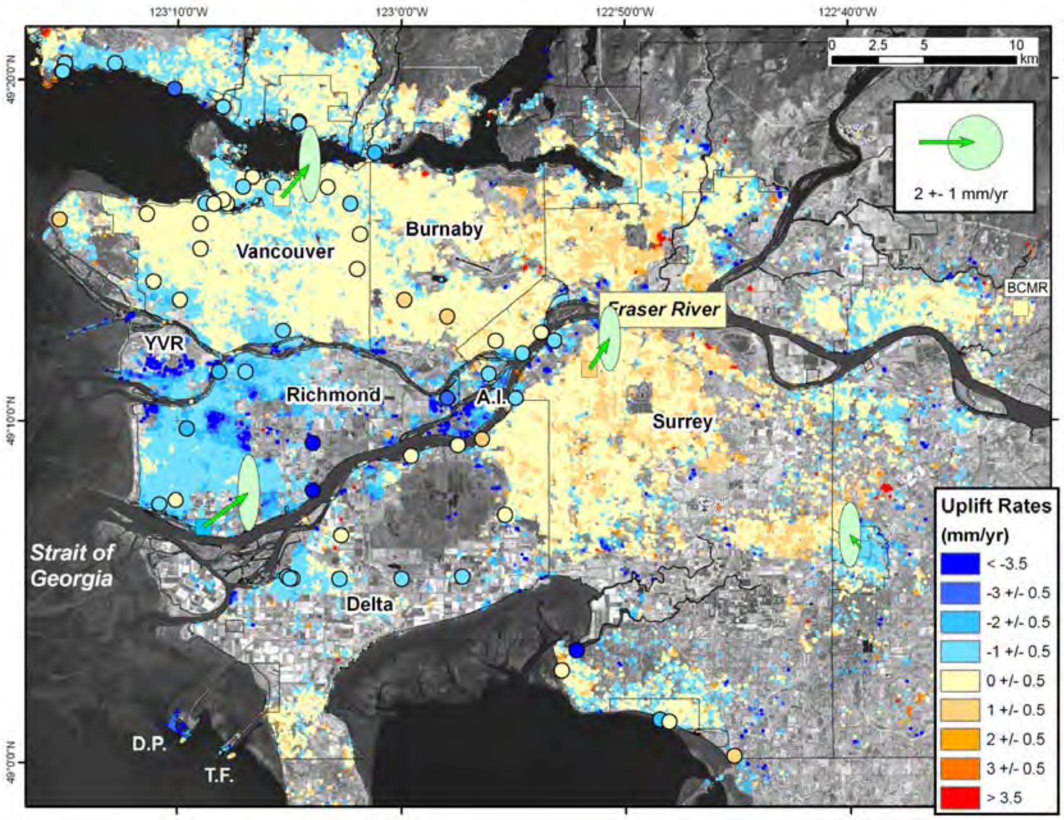

Figure 10. Vertical land motion in the Fraser Delta-Greater Vancouver area. Vertical velocities based on InSAR (map), leveling (circles) and GPS squares are colored coded: blue=subsidence, yellow=stable; orange=uplift (modified after Lambert et al., 2008 and Mazzotti et al., 2008a.)

3.4. REGIONAL SEA LEVEL CHANGE

In addition to changes in relative sea level due to changes in land elevation (e.g., tectonic, GIA, and sediment compaction processes), sea levels in British Columbia vary spatially and temporarily due to synoptic, seasonal, interannual, decadal and secular changes in ocean circulation, wind velocity, atmospheric pressure, and water mass distribution and properties. Changes associated with currents, wind, and atmospheric pressure can be termed *dynamic* effects while those associated with water properties are termed *steric* effects. All factors exhibit a dominant annual cycle (e.g., Figure 11) related to regional changes in solar heating and significant low frequency variability due to events in the open Pacific Ocean.

Sea level varies on the order of 0.1 to 0.5 m at synoptic (~ 1 to 30 day) time scales due to passing low pressure systems and associated winds (Abeysirigunawardena, 2007; Tinis, 2008). Strong northwesterly winds and high atmospheric pressure associated with “fair weather” conditions during summer can also lead to marked sea level variability on the British Columbia coast. Specifically, prevailing northwesterly (equatorward) alongshore winds in summer combined with high atmospheric pressure and equatorward coastal currents normally lower coastal sea levels by ~0.1 m (Figure 11) whereas prevailing southeasterly (poleward) alongshore winds in winter combined with low atmospheric pressure and poleward coastal currents normally increase coastal water levels by 0.1 m. A more detailed discussion of extreme water level changes is presented in Section 5.

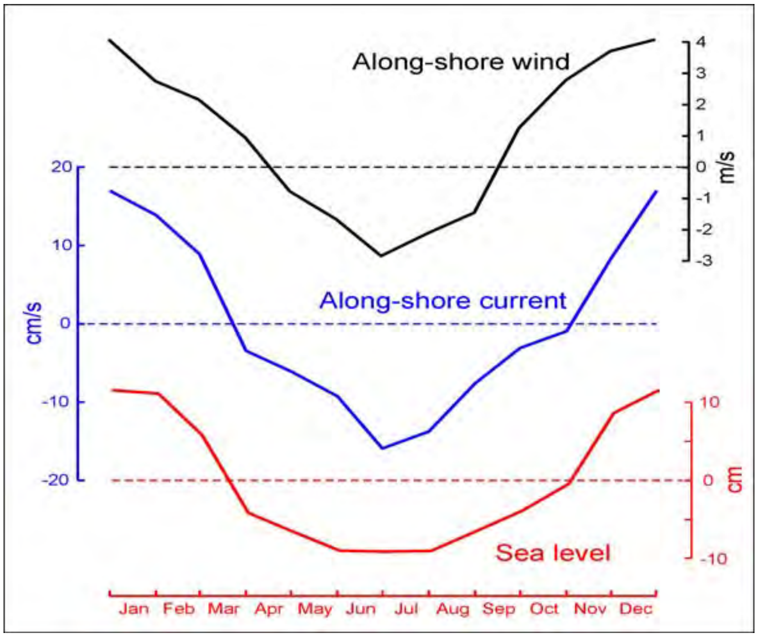

Figure 11. The mean annual cycles in wind, current and sea level for southwest Vancouver Island. (a) the monthly alongshore wind velocity measured on the continental shelf; (b) the monthly alongshore component of ocean current at 35 m depth on the continental slope; and (c) the mean-removed monthly sea level at Tofino adjusted for the inverse barometer effect. (Modified after Krassovski, 2008).

Decadal-scale variability in regional sea level due to changes in currents, water temperature, and atmospheric conditions are primarily linked to ENSO (El Niño-Southern Oscillation) and PDO (Pacific Decadal Oscillation) fluctuations while long-term trends are linked to climate-induced changes in ice melt and ocean water properties. El Niño events occur at a frequency of between 2 and 7 years in the tropical Pacific region, with a persistence ranging from 6 to 18 months. However, only major ENSO events (such as the most recent events in 1982/83, 1991/92 and 1997/98) have a pronounced impact on the British Columbia coast (cf., Subbotina, 2001). The PDO variability is typically over time scales of 20-30 years. These two cycles interact to intensify or diminish oceanographic effects in coastal areas, such as sea surface temperature, sea levels and storminess. For much of the 20th Century, ENSO events occurred at intervals of 15 to 25 years. However, according to some authors, since 1976 ENSO events have become more intense and frequent with effects lasting longer (Trenberth and Hurrell, 1995; Timmerman, 1999). Off the coast of Oregon, Washington and British Columbia, documented low-frequency sea level changes are in the range of 0.30 to 0.40 m above the monthly mean values and more than 0.2 m above the maximum monthly mean sea level during intense El Niño events (Thomson and Tabata, 1989; Komar, 1992; Thomson and Crawford, 1997; Kaminsky et al., 1998; Canning, 2001; Subbotina, 2001). In 1997-98, Hecate Strait had sea levels ~0.4 m higher than normal (Barrie and Conway, 2002; Walker 2007).

Steric sea level (derived from the depth-integrated water density) varies temporally due to seasonal, interannual, decadal and secular changes in local water density. Changes in both water temperature (“thermosteric” change) and salinity (“halosteric” change) contribute to the total steric variations in the ocean (the procedure for calculating steric values from the observed specific volume anomaly can be found in Thomson and Tabata, 1987). The annual cycle in surface ocean heating and cooling, combined with the annual cycle in precipitation and river runoff, atmospheric (including winds) and ocean circulation effects, give rise to a marked peak-to-trough cycle in annual sea level variability of around 0.2 m (20 cm) depending on the region and the reference depth selected for the calculation (Figure 11).

Determination of long-term, climate-scale changes in steric height requires the accurate measurement of temperature and salinity from repeated conductivity-temperature-depth (CTD) profiles from a ship or other surface vessel. The depth-integrated density variations relative to a specified depth (e.g., 1000 m) due to thermosteric and halosteric contributions generate the density-induced total steric effect. Results from Station "P" (located at 50^o N, 145^o W, 1500 km westward of the British Columbia coast in the central northeast Pacific) from 1956 to 1986 yielded a long-term steric sea level trend of 1.1 mm/year relative to 1000 m depth, of which 67% was due to thermosteric effects and the remaining 33% to halosteric effects (Thomson and Tabata, 1989). A revisit to this study which is presently underway using data from Station "P" up to 2007 is yielding a similar partitioning of the thermosteric and halosteric effects but with a somewhat higher long-term total steric rise indicative of a more accelerated climate-change in the northeast Pacific since 1986.

We have also used the extensive CTD time series collected by the Canadian Navy at the Nanoose Bay Naval Test Range to examine steric sea level changes in the Strait of Georgia from 1979 to 2007. (The CTD time series begins in 1969 but consisted of only a few profiles per month prior to March 1979 when profiles were collected at hourly to daily intervals.) As indicated by Figure 12, steric sea level fluctuations in the Strait of Georgia relative to the near-bottom depth of 300 m consist of high-frequency (~daily) fluctuations with a peak-to-peak range of a few centimeters superimposed on pronounced annual and decadal-scale cycles each with ranges of around 20 cm. Peak steric sea levels tend to occur in summer and minima in winter. Over the roughly 30-year time series, maximum steric levels in the strait occurred in summer at the times of major 1982/83 and 1997/98 ENSO events while minimum steric levels occurred in winter several years after the ENSO events. As indicated by Figure 12, roughly 63% of the long-term steric height rise in the central Strait of Georgia is due to changes in salinity rather than changes in temperature. This is the reverse of offshore stations. At the dominant annual cycle, the ratio of thermal to salinity changes is 0.55, whereby the thermosteric effect accounts for only about 35% of the total annual steric height variability. The trend in the total steric height is estimated to be 1.19±0.09 mm/year, which is not inconsistent with the global mean thermosteric trend of 1.60 ± 0.50 mm/year for 1993 to 2003 reported by IPCC (2007). However, for the Nanoose time series, only about 35% of the total steric change is due to thermosteric effects, with the other 65% arising from halosteric changes. We note that, in addition to the annual and decadal signal, the halosteric contribution also contains a strong semiannual component associated with increased river discharge in summer and increased rainfall in winter. This component accounts for the greater contribution of the halosteric effects to the amplitude of the annual component and for the phase shift between the halosteric and thermosteric effects through the year. Despite the significant halosteric component of sea level rise in the Strait of Georgia, the rate of total steric rise falls below that reported for the World Ocean (IPCC, 2007). Equally problematic is the fact that the observed steric height rise in the strait is counter to what would be expected on the basis of the near zero trends in relative sea level rise observed at the Point Atkinson, Vancouver, and Cherry Point tide gauge stations. Further research is needed to resolve these contradictory findings and is beyond the scope of this report.

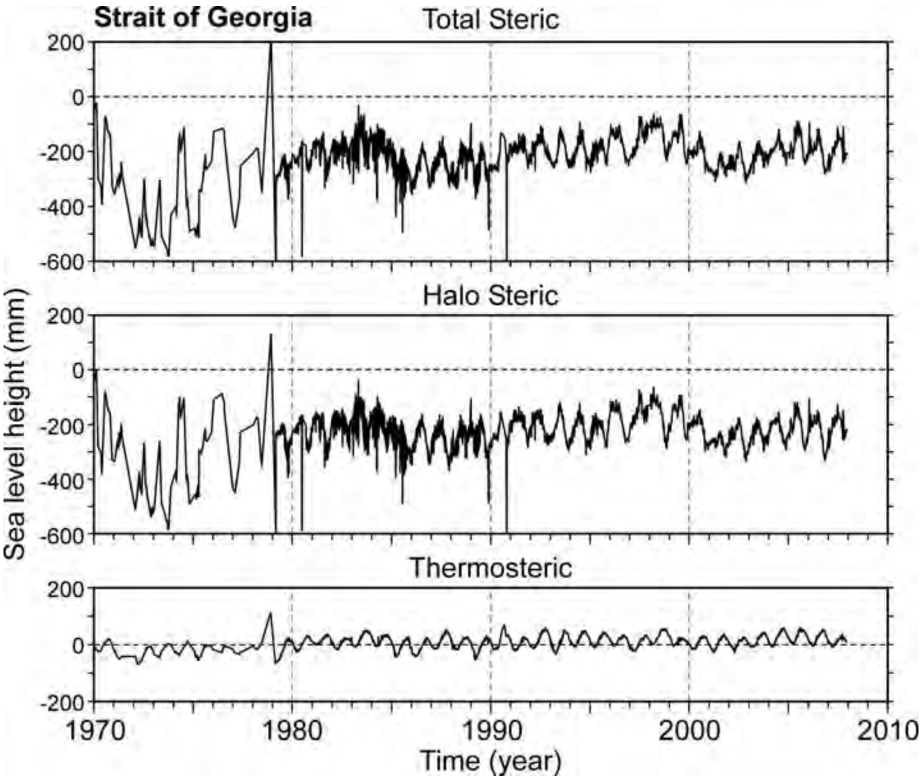

Figure 12. Steric sea level in the Strait of Georgia off Nanoose Bay, 1979 to 2007 (referenced to 300 m depth). (a) Total steric height; (b) halosteric height; and (c) thermosteric height. (Thomson et al., in preparation).

4.0. FUTURE SEA LEVEL CHANGE

Predicted changes in relative sea level for coastal British Columbia are dependent on predictions of eustatic sea level rise in the World Ocean associated with melting of continental ice sheets, water impoundment in reservoirs, and global ocean thermal expansion, coupled with predictions of more regional changes in relative sea level that incorporate the effects of local oceanographic, and tectonic processes and sediment compaction. Details of each factor are described below and projected changes in relative sea level based on tide gauge and GPS measurements for the Alaska-British Columbia-Washington region are presented in Appendix A.

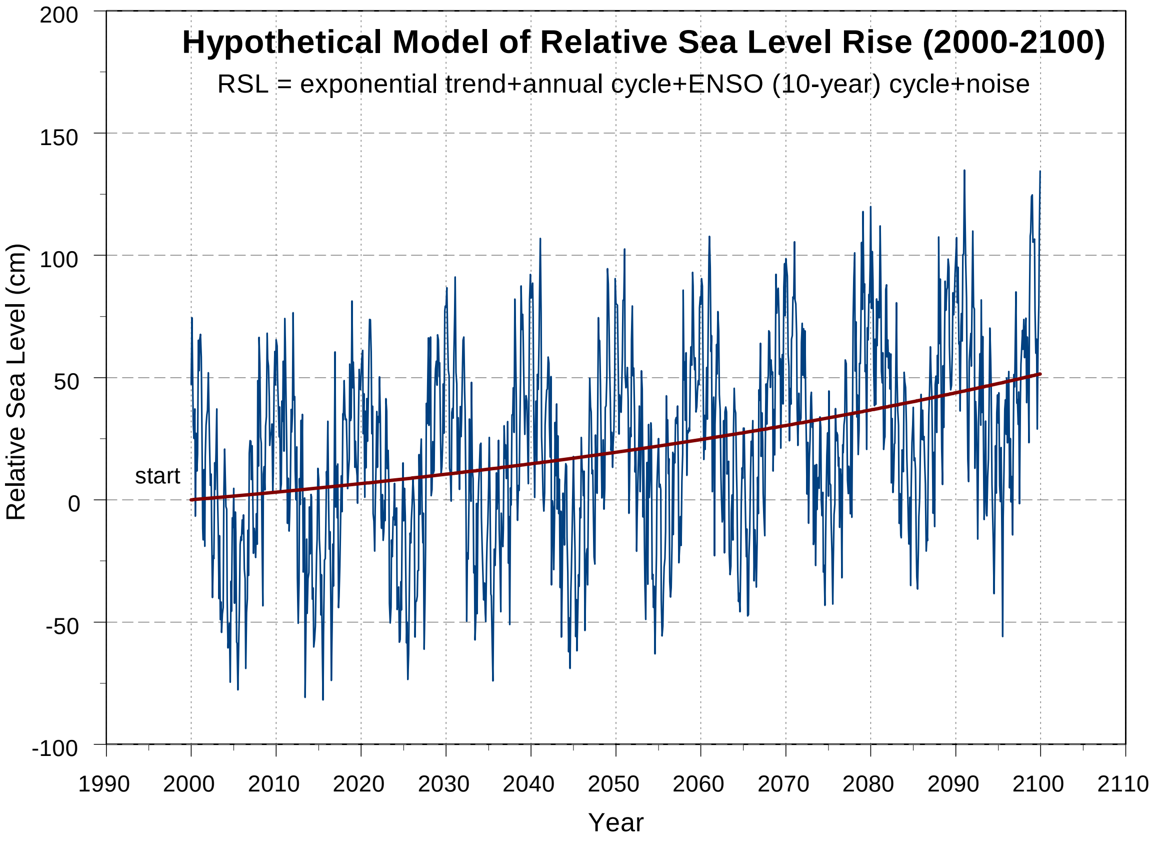

Figure 13. Results of a hypothetical model of monthly mean relative sea level rise consisting of an exponential increase in mean sea level of 50 cm by 2100. Superimposed on the trend is an annual cycle of monthly mean sea level variability that peaks around January 1 with a maximum elevation of 30 cm, a 10-year ENSO cycle that peaks in late winter with an elevation of 40 cm and a random error with normal distribution, mean = 0 and standard deviation = 10 cm. Tides and geodynamic effects have been excluded. Random components have been added to the amplitudes of the annual and ENSO cycles and to the phase of the ENSO cycle. When measured relative to the original datum level of “0 cm” at the start of the record, the monthly mean heights of extreme winter sea level events increase with rising eustatic sea level but the number of such events during each decade does not increase in a simple uniform manner.

4.1. GLOBAL SEA LEVEL PROJECTIONS

IPCC (2007) presents projected global average sea level rise for six "emissions marker scenarios" (Table 2). The range of global sea level rise at the 90% confidence interval lies between 0.18 and 0.59 m by 2100 (i.e., there is a 90% probability of the "true" value lying in this range).

Mote et al. (2008) point out, however, that cryospheric contributions are likely to be significantly greater than the IPCC assumptions and put greater weight on more recent satellite-based observations. In their analysis of projected sea level rise for Washington State, they present an estimate of 0.34 m as an upper limit of ice sheet contributions to sea level rise by 2100; thus, their maximum total sea level rise estimate is 0.93 m. Mote et al.'s (2008) estimates are a logical global baseline upon which regional effects (local steric, isostatic, geodynamic and atmospheric) can be built for sections of the British Columbia coast. However, the present report is meant to be a "stand-alone" document that does not depend on the estimates of Mote et al. (2008) for a more southern portion of the North American coast.

Of the projected global sea level change by the end of the 21st Century predicted in Table 2, the range of contributions from global thermal expansion (thermosteric effects) is estimated to be 0.17 ± 0.07 m (1.7 ± 0.7 mm/year) for scenario B1 to 0.29 ± 0.12 m (2.9 ± 1.2 mm/year) for scenario A1F1, accounting for nearly half of the *total* predicted sea level rise in the IPCC (2007) report.

Rahmstorf et al. (2007) point out that, between 1990 and 2007, global mean sea level has risen faster than predicted by the IPCC (2007) report (3.3 mm/yr versus 2.0 mm/yr). Although this estimate is based on a very short time series, it is consistent with observations of global mean temperature that also suggest a rise at the upper limit of the IPCC prediction range. Based on an empirical relationship between global mean sea level change and global mean surface temperature, Rahmstorf (2007) suggests that projected sea level in 2100 could be as high as 0.5 to 1.4 m, about 2-3 times larger than the IPCC (2007) predictions.

IPCC Scenario	**The 90% probability range of Sea Level Rise (at 2090-2099 relative to 1980-1999) *excluding* future rapid dynamical changes in ice flow (m)**
B1 – same population as A1, rapid changes in economic structures, move to service/information economy	0.18-0.38
A1T –non-fossil energy technologies	0.20-0.45
B2 – intermediate population and economic growth, emphasis on local solutions to economic/social/environmental sustainability	0.20-0.43
A1B – balance of energy sources/technologies	0.21-0.48
A2 – high population growth, slow economic development, slow technological change	0.23-0.51
A1F1 – fossil intensive energy sources	0.26-0.59

Table 2. Projected global average sea level rise at the end of the 21st Century (IPCC, 2007). All A1 scenarios are for a world of rapid economic growth, a global population peaking in about 2050, and rapid development and implementation of new energy-efficient technologies. The subdivisions of A1 describe the possible alternative directions of technological change.

While Rahmstorf's (2007) conclusions have been questioned (Holgate et al., 2007; Schmit et al., 2007), they are consistent with concerns raised by other researchers regarding the underestimation by IPCC (2007) of future polar ice sheet melting and global sea level rise (Overpeck et al., 2006). The research by Rahmstorf and colleagues highlights the range of uncertainty which remains today with respect to projections of future sea level rise.

4. 2. REGIONAL EFFECTS

4.2.1. Atmospheric Circulation Effects

In addition to the above estimates for the possible range of global average sea level change during the 21st Century, there are equally important regional effects which will govern what occurs along the coast of British Columbia. Mote et al. (2008) point out that changes in atmospheric circulation accompanying general warming could lead to regional changes in sea level. At present, mean winter sea levels along the coast of Washington are about 0.5 m higher than summer levels, a result of the dominantly southerly winds in the winter; during major El Niño events, sea levels can be further raised by another 0.3 m for several months (Ruggiero et al., 2005).

Hannah and Crawford (1996) show that during winter in Hecate Strait, sea level responds to both large-scale and local wind forcing. They further show that the large-scale and the local wind forcing were of roughly equal importance and that the fluctuations were associated with a particular spatial pattern in the velocity field. Thus, any long-term changes in the positions and durations of atmospheric high and low pressure cells could, conceivably, give rise to changes in mean annual sea level. The jet stream, the meandering band of strong winds near the troposphere which is important in controlling the location and trajectory of synoptic-scale disturbances at mid-latitudes, is also likely to adjust in response to climate change. According to Archer and Caldeira (2008), the jet stream in the northern hemisphere rose in altitude, moved poleward and weakened in intensity over the study period from 1979 to 2001. Such changes in the jet stream location, intensity, and altitude lead to variations in the frequency and intensity of storms. According to the authors, "Further observations and analyses are needed to confidently attribute the causes of these changes to anthropogenic climate change, natural variability, or some combination of the two". What effect changes in the jet stream have on storm surges and sea levels on the BC coast has yet to be determined.

One of the potential consequences of a regional change in atmospheric circulation would be a change in upwelling intensity and, as a result, in the water temperature and salinity in the region of upwelling. Due to wind-driven offshore surface water transport during upwelling, coastal sea surface "set-down" occurs and can have magnitudes of 10s of centimeters near a coast. The resultant compensating onshore transport of more dense water at depth adds a steric effect which augments the wind-driven set-down and further lowers relative sea level. As an example, McGregor et al. (2007) describe the rapid 20th Century increase in upwelling intensity off northwest Africa due to changes in the atmospheric pressure gradient between coastal areas and the northwest African continental interior. Sea surface temperatures were diminished by approximately 1.2 °C during the century. In the case of Northwest Africa, the authors conclude that upwelling is expected to intensify further during global warming, presumably leading to further decreases in relative sea level in that area.

Mote et al. (2008) averaged the results of 18 models (for IPCC moderate greenhouse gas emission scenario A1B) with respect to anticipated changes in sea level as a result of ocean density and atmospheric circulation effects by the end of the 21st Century compared to the period 1980 to 1999; for the coast of North America they predict an annual mean sea level 2-3 cm (0.02 to 0.03 m) *below* the global mean (Figure 14).

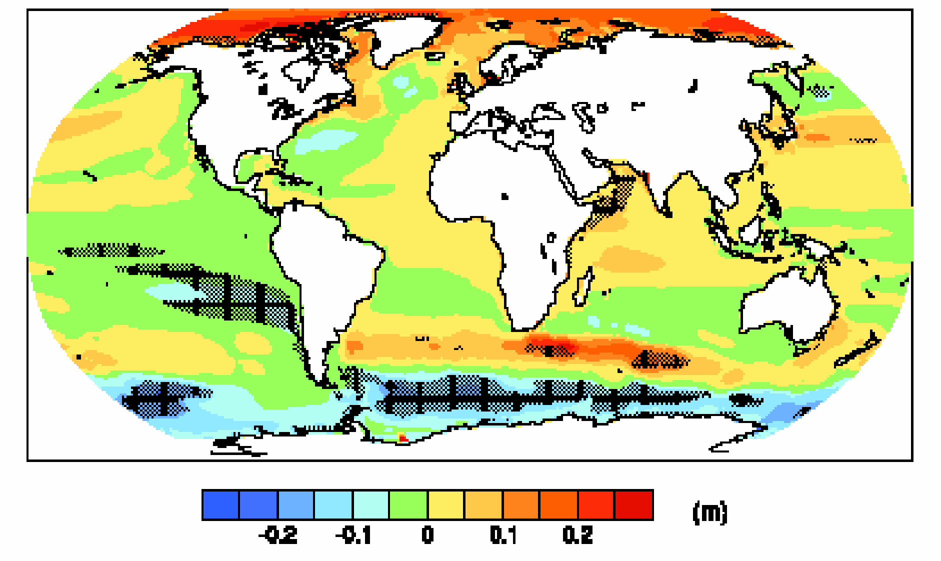

Figure 14. Regional sea level changes [(2080-2099) minus (1980-1999)] as a result of sea water density differences and atmospheric circulation effects. Results are based on 18 models using the A1B emissions scenario. Note that the area off western North America shows a *decrease* in sea level from these two sources of 0.0 to 0.05 m relative to the global average (IPCC, 2007).

Based on 30 scenarios from the IPCC global climate models, Mote et al. (2008) report, a broader range of possible regional effects. Changes in the winter wind regime over these 30 scenarios were found to be minimal, leading the authors to subtract 2 cm (0.02 m) from the “very low” sea level rise scenario for 2100; for the “medium” sea level rise estimates, they consider the winter changes to be negligible. For the “very high sea level rise” scenarios, they conclude that several models show an increase in sea level of 0.15 m by 2100 above global mean values. Ignoring vertical land movement, the Mote et al. (2008) estimates translate into sea level changes along the Washington coast of 0.16 m, 0.34 m and 1.08 m by 2100 for their “very low”, “medium” and “very high” sea level rise scenarios, respectively. The authors further state that: “Both the very low and very high SLR estimates are considered low probability scenarios” (p. 10). They explicitly point out, however, that they have not attempted to quantify probabilities or uncertainties. Based on the Mote et al. (2008) results and interpretations, we infer that their *most likely estimate of mean sea level rise by 2100* along the Washington (and southern British Columbia) coast, ignoring regional vertical land movement, is 0.34 m (their “medium SLR” scenario), with no regional atmospheric or oceanic circulation effects.

While attempts have been made to predict the relationships among long-term atmospheric trends, ocean circulation and sea levels, the problem is fraught with complexities which have not yet been completely addressed. To quote the Earthguide (University of California at San Diego) (2002): “… how will the ocean's circulation respond to climate change? Although this sounds like a simple question, answering it is difficult. The ocean responds largely to winds, and wind fields respond to the distribution of heat, which depends on the ocean circulation. Within a logic loop like this, where the final answer depends on the initial guess, any small errors can be readily amplified into large errors in the prediction game.” As a recent example of this complexity, Thomson et al. (2007) have shown that strong southerly winds off western Washington in winter can lead to prolonged periods of current reversal in the normal estuarine circulation in Juan de Fuca Strait. These wind-induced reversals can last up to a week and lead to a coincident relative sea level rise of the order of 0.1 m in the Strait of Georgia. Under climate change scenarios such episodes could become more frequent and/or more intense.

4.2.2. Regional Long-term Steric Effects for British Columbia

In addition to long-term changes in ocean circulation, freshwater input to the British Columbia coast also has an influence on sea levels through changes in seawater density. The results of regional climate and watershed modeling are thus required in order to assess the seasonal and long-term effects from changes in freshwater input from coastal drainage systems. Two of the most significant freshwater inputs to coastal British Columbia waters are the Fraser River and the Skeena River. The Fraser River discharges approximately 144 km^3/year into the Strait of Georgia (Dai and Trenberth, 2002), ranking 30th among world rivers; the Skeena River discharges 36 km^3/year into Hecate Strait and ranks 87th among world rivers. Figure 15 and Table 3 show changes which have occurred in precipitation patterns since the middle of the 20th Century in British Columbia.

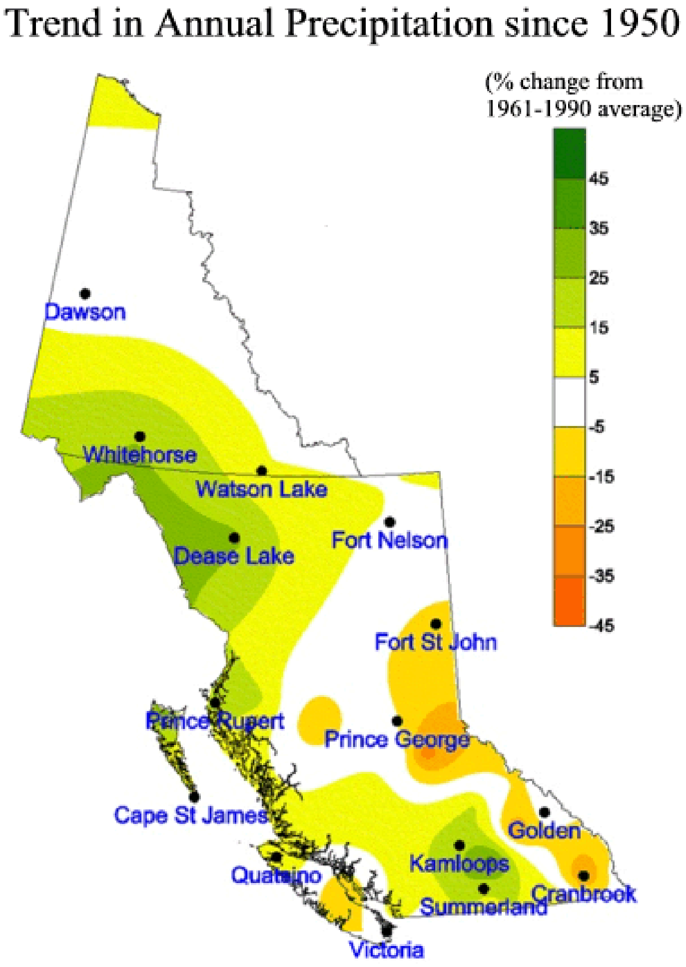

Figure 15. Trends in annual precipitation over the last half of the 20th Century (Environment Canada 2004; http://www.ecoinfo.org/envind/region/climate/climate e.cfm)

Precipitation Trend 1950 to 2001	Winter	Spring	Summer	Autumn	Annual
Victoria	-16.75	13.26	-3.86	-3.33	-3.11
Quatsino	-1.12	22.17	**31.19 +**	14.35	12.82
Prince Rupert	3.49	2.54	11.53	**30.71***	**18.46***

Table 3. Precipitation change (%) at three coastal British Columbia sites between 1950 and 2001. Here, + indicates $P < 0.10$; * indicates $P < 0.05$.

Taylor and Taylor (1997) concluded that since the 1960s the annual flow of the Fraser River has been falling and that more of the total volume is occurring earlier in the year.

Whitfield (2003) analyzed changes in runoff patterns from some B.C. rivers during part of that interval. Figure 16 shows the change in Fraser River runoff between 1976 and 1995; while overall discharge has not changed appreciably, there has been a shift to greater flow in the earlier spring and overall lower flow in the late summer and early autumn (Leith and Whitfield, 1998). Similar patterns were also observed in coastal rivers (Whitfield and Taylor, 1998). Unfortunately the record of observations is too short to be meaningful with respect to longer term climate change, and could simply reflect decadal fluctuations, but does support the trend toward earlier peak flow periods shown in the predictions of Morrison et al. (2002) (see below).

In general, since 1950, the seasonal precipitation trends have been toward wetter springs and summers for southern and coastal British Columbia, and significantly wetter autumns in northern coastal British Columbia (Figures 17 and 18). Climate modeling predicts that, by the winter of 2050, precipitation in many coastal British Columbia areas, and within substantial parts of the major watersheds (i.e., Fraser and Skeena), will rise by 10-25 %; in summer most southern areas will become drier, though a large part of the North Coast and the watershed of the Skeena will experience precipitation increases of up to 20 % .

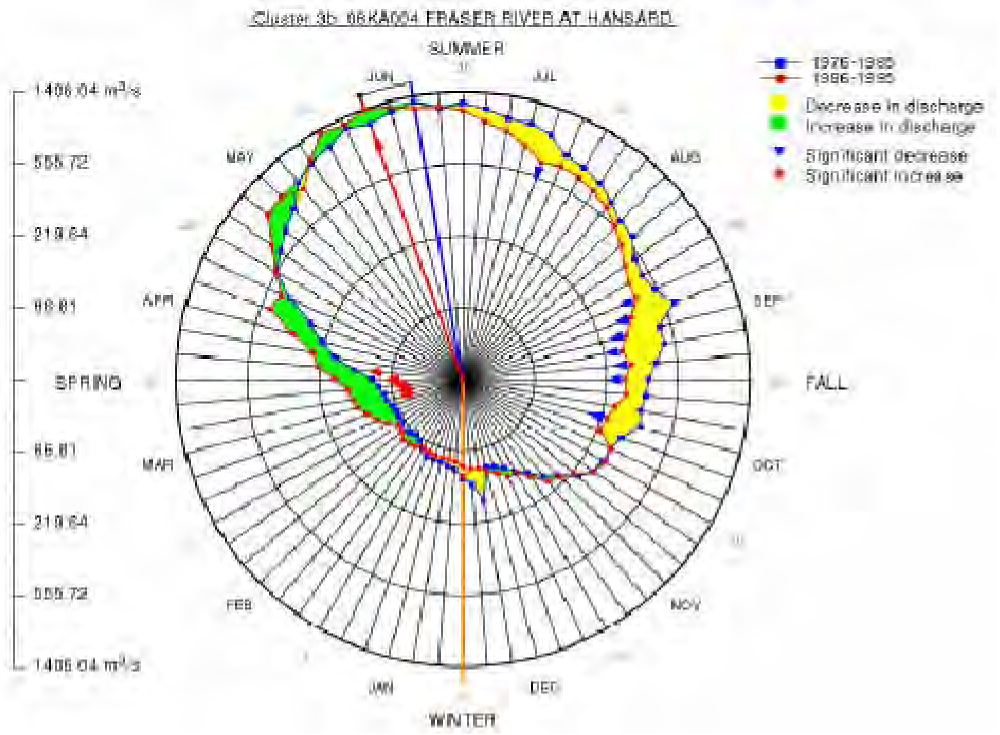

Figure 16. Fraser River discharge between 1976 and 1995. Note the shift to higher discharge in March and lower discharge in July and September (after Whitfield, 1997).

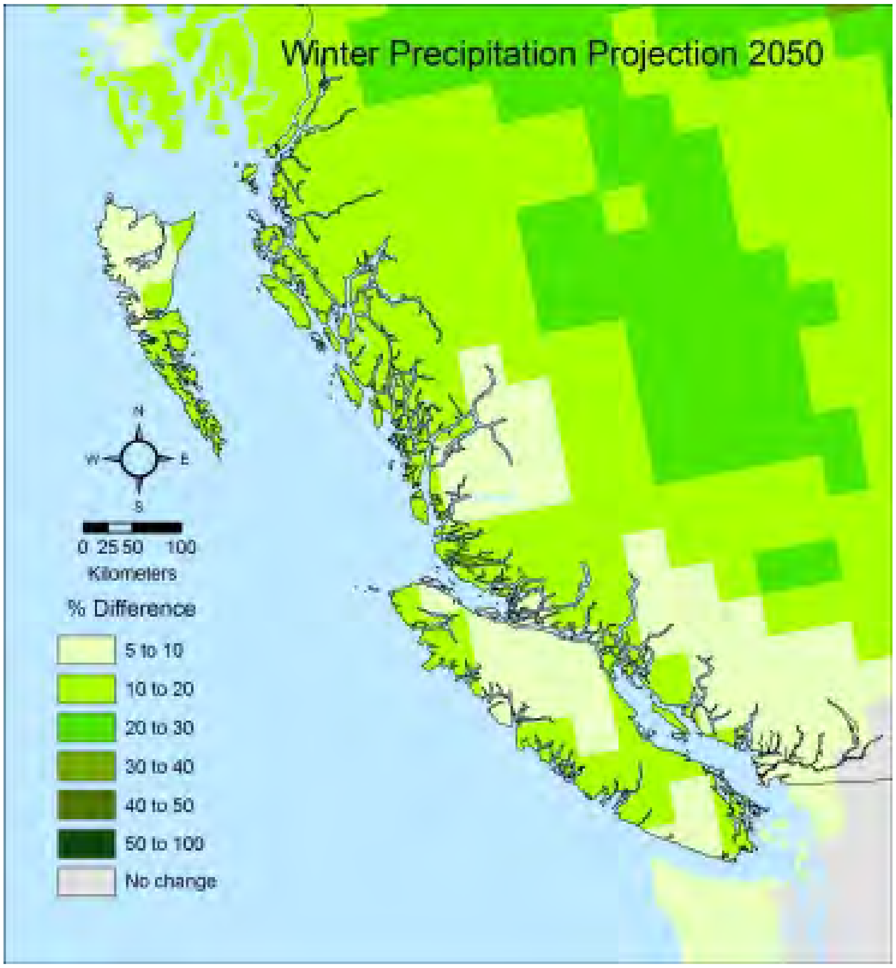

Figure 17. Predicted percentage change in winter precipitation by 2050 relative to mean values from the period 1961-1990. Canadian Regional Climate Model 4.1.1, SRES-A2 scenario (April 2007) (http://www.pacificclimate.org/resources/climateimpacts/ bccoast/).

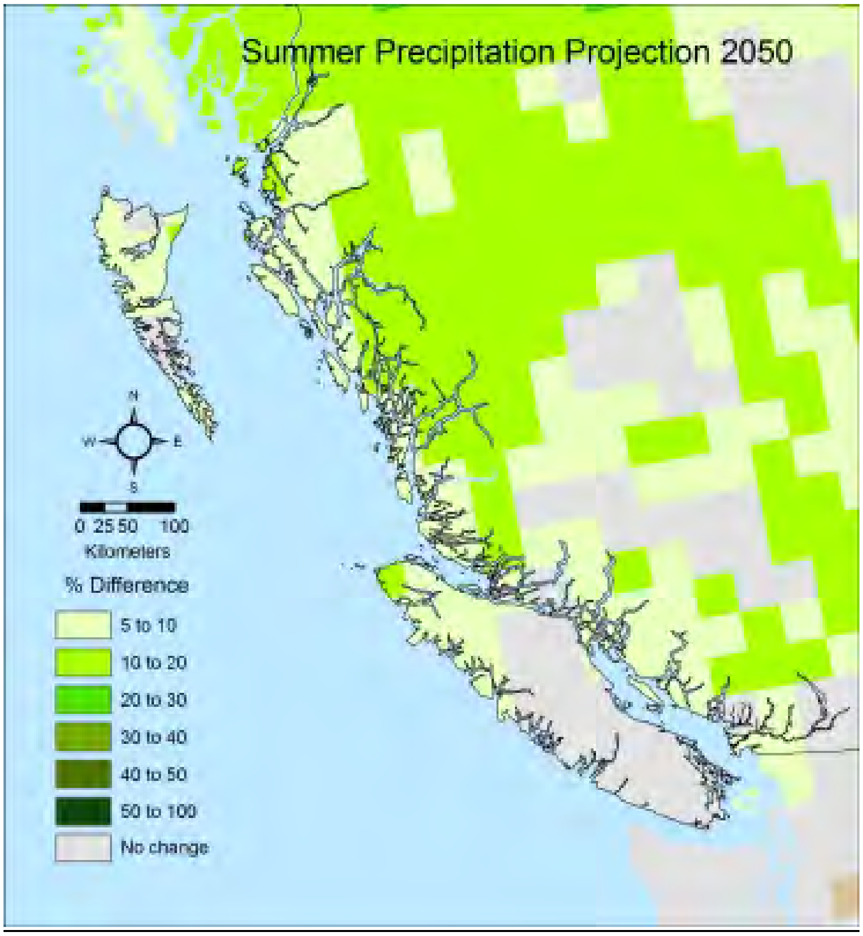

Figure 18. Predicted change in summer precipitation by 2050 relative to mean values for 1961-1990. (http://www.pacificclimate.org/resources/climateimpacts/bccoast/). Based on climate modeling results from the Pacific Climate Impacts Consortium, SRES-A2 scenario (April 2007).

Clearly, the consequences for freshwater contributions to coastal waters of British Columbia require a full hydrological assessment of anticipated changes under various climate scenarios for the major coastal watersheds. To date, this has not been done, although attempts to model the Fraser River discharge and some Vancouver Island watersheds have been undertaken. Morrison et al. (2002) investigated likely flow scenarios for the Fraser River watershed for the 21st Century. Their modeling was based on Coupled General Circulation Models (Canadian Centre for Climate Modeling and Analysis CGCM1 and the Hadley Centre for Climate Prediction and Research HadCM2) downscaled to sites in the Fraser River watershed for which there were reliable long-term weather data. The atmospheric variables considered in their model include wind speed, solar radiation, cloud cover, temperature change, precipitation, and vapor pressure. Results show that by 2080 there would be a significant increase in flow in spring (March-April) but a decrease in flow in early summer (May-June), the time of today's freshet. Thus, one of the most significant findings from their analysis is a change in the *timing* of the flow, with higher values occurring earlier in the year. Overall, the model predicts only about a 5% change in the mean or minimum flow characteristics of the Fraser River. The models do, however, predict a decline in *peak* flow for the end of the 21st Century compared with the 1970-1979 baseline. At present, flow increases in spring through snowmelt, reaching a mean peak in mid-June of about 8,000 to 10,000 m^3/s. By 2080, however, 13 % of the years will no longer be snowmelt-dominated and will experience peak flows much earlier or later (possibly as early as April or as late as mid-October) in response to rainfall events. These peak flows are expected to reach maxima of about 5,000 to 6,000 m^3/s, a decrease in average peak flow of about 18 % (1600 m^3/s) below the current values (Figure 19).

Another factor which will continue to influence Fraser River hydrology over at least the next several decades results from the infestation by the Mountain Pine Beetle, which currently affects about 10 million hectares. The result is a sharp increase in peak flow volumes for small watersheds and an advance in the timing of freshets (Forest Practices Board BC, 2007).

There is unlikely to be a significant impact on mean halosteric (salt induced) sea levels in the Strait of Georgia from such a modest increase in annual flow from the Fraser River. On the other hand, there could be a potential change in the seasonal distribution of effects compared to today as a result of the decrease in peak flow related to the snowmelt freshet and to the related distribution of rainfall-dominated flow throughout a longer period of the year. Based on our analysis of the 30-year temperature-salinity time series from the Nanoose Bay test range (Section 3.4), peak annual contributions from temperature variations in the water column occur in late August and therefore lag those from salinity contributions in late spring by about 3 months. An increase in the lag between the thermosteric and halosteric contributions to the total steric sea level rise could lead to a diminished seasonal contribution to steric sea level variations in the Strait. The uncertainty is high since, in addition to the change in the timing of peak flows, there is expected to be a change in the temperature of river water which would have an effect on the temperature of coastal waters and thereby on steric sea level elevations. To date, no modeling of the consequences of either of these impacts for the Strait of Georgia region has been undertaken.

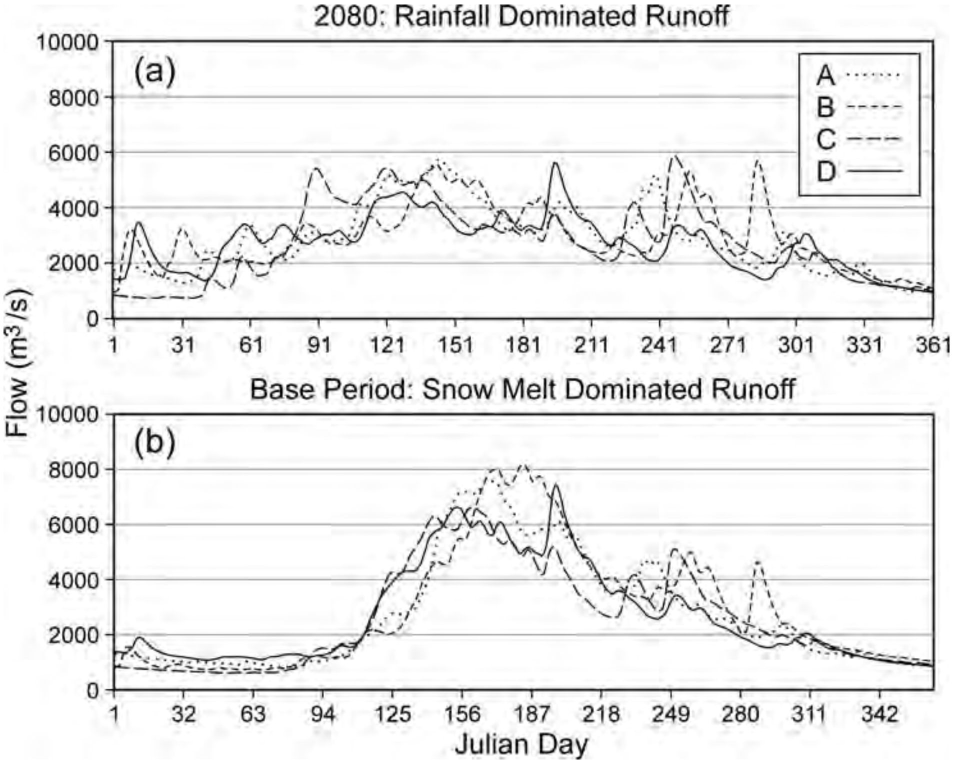

Figure 19. Model results for four annual discharge scenarios for the Fraser River which show the consequences of a shift in peak flow from snowmelt freshet (b) today to predicted rainfall-driven (a) peak discharge events in 2080. Note the broader distribution of peaks in flow throughout the year (March through October) in 2080 compared to the snowmelt-related peak discharge in June. (With permission from Morrison et al., 2002).

On the North Coast, the potential for regional steric sea level impacts would theoretically appear to be greater than for the South Coast, given the anticipated 18.5 % increase in precipitation which has occurred between 1950 and 2001 (Table 3) and the predicted 10-20 % increase by 2050 compared to the 1961-1990 baseline (Figure 17, 18). Coulson (1997) in his analysis of changes over the last part of the 20th Century in northern British Columbia shows that there has been shift towards earlier snowmelt and higher discharges in the spring for rivers including the Skeena. The analysis suggests that, under climate change scenarios, flows in northern rivers would increase in the spring, with an earlier freshet, and with slight increases in flow during summer (as opposed to decreases in southern rivers). Although no other definitive studies related to the hydrology of northern British Columbia rivers under climate change scenarios appear to exist in the recent literature, the qualitative findings of Coulson (1997) for British Columbia rivers have been supported by more recent modeling studies for southern coastal watersheds (e.g., Morrison et al., 2002).

While volumetrically less important than the two large British Columbia watersheds, smaller coastal river systems also contribute to the fresh water input to coastal waters. Few analyses of anticipated changes in flow regime of such rivers have been undertaken. One example is that of the Englishman River on Vancouver Island (Weston et al., 2003) which predicts that peak annual flows in 2080 will be 17 % greater than present, with more frequent flood events. The authors conclude that, by 2080, the magnitude of the 10-year flood will be equal to today's 20-year flood. These changes are based on a predicted 65 % decrease in snowfall and 35 % increase in rainfall within the watershed by 2080-2100.

What effect changes in river discharge volumes and timing have on steric sea level in semi-enclosed basins such as the Strait of Georgia is unknown because it is unclear how the estuarine circulation – which ultimately carries the freshwater seaward in the upper outflow layer – will respond to the change in freshwater flux.

4.2.3. Predicted Vertical Land Movements on the British Columbia Coast

Predictions of vertical land motion during the 21st century are mainly based on extrapolations of measured trends at GPS and tide gauge stations, the latter corrected for a regional sea level trend in order to account for the contribution from land motion (cf. Mazzotti et al., 2008b). This extrapolation assumes that trends of vertical land motion measured over the last 5 to 50 years will remain constant over the next century. Most GPS stations are installed on stable bedrock and are thus representative of long-term geological deformation of the crust, which can be approximated as steady-state over decades to centuries. Tide gauges can be more problematic in that some are installed in coastal or harbour sediments which may undergo non-linear compaction and settlement effects over years to decades. However, a comparison of GPS and tide gauge vertical land motions at nearby sites indicates a good agreement between the two observational methods at more than half of the closely co-located sites (Mazzotti et al., 2008b).

In addition to the steady-state extrapolation of regional trends, two cases must be considered: (1) the local effects related to sediment compaction, ground-water changes, and local tectonics; and (2) the effect of a very large earthquake, such as a magnitude ~9 Cascadia subduction earthquake. The only well-documented case for local land motion variations (Case 1) is that of the Fraser River delta presented in Lambert et al. (2008) and Mazzotti et al. (2008a). As summarized earlier, these studies reveal an average ongoing subsidence of the Fraser River delta of 1-2 mm/yr due to steady-state compaction of the first 10 to 30 m of Holocene sediments that cover the delta lowland. This background estimate can be extrapolated over the next 100 years to provide a total subsidence of 10-20 cm by 2100. In some regions, faster subsidence rates up to 10 mm/yr are associated with major construction activity, such as that associated with the Vancouver International Airport and the BC Ferries Tsawwassen terminal. In these cases, the extrapolation of the total subsidence over 100 years must take into account the non-linear response of sediments to load. Mazzotti et al. (2008a) found that a first-order time constant of ~20 years was appropriate for the sample of structures they analyzed. They concluded that the "difference between natural and anthropogenic compaction results in strong spatial variations of present and future RSL rise across the Fraser River delta, with small zones experiencing RSL rise up to 80-100 cm within larger areas experiencing a natural RSL of 40-70 cm."

Details on the impact of a great magnitude ~9 earthquake are discussed in Section 3.2. The main conclusion is that such an event would result in sudden subsidence and a relative sea level rise of 0.5 to 2 m along the west coast of Vancouver Island, with a rapid eastward decrease of predicted amplitudes. Estimates of the changes in relative sea for Victoria and Vancouver range between 0 and 20 cm. For the northern part of Vancouver Island, the impact of a magnitude ~9 Cascadia earthquake would be small, likely less than 10 to 20 cm of subsidence and relative sea-level rise depending on the distance to the Cascadia offshore fault.

4.2.4. Predicted changes in ENSO events

The debate on how the tropical Pacific will respond to global warming continues to ask whether the changes in the ocean surface temperature structure will more closely resemble an El Niño or a La Niña (Vecchi et al., 2008). This distinction is of considerable importance to coastal British Columbia since conditions in the tropical Pacific affect a wide range of weather and oceanic phenomena including tropical cyclones activity, global patterns of drought and flood, agricultural productivity, coastal upwelling and ocean productivity. Whether the changes are El Niño-like or La Niña-like could markedly affect how the atmospheric and oceanic conditions off coastal British Columbia respond to the climate-induced change. Here, the terms El Niño-like or La Niña-like refer to the tendency for the time-averaged sea surface temperature gradient in the equatorial Pacific to either decrease (El Niño-like) or increase (La Niña-like), without implication for changes in the intensity or frequency of variability. Unfortunately, the science remains in a state of flux. As noted by Vecchi et al. (2008): “Theory, models, and observations present diverging views of the Pacific response to global warming. It may be possible to reconcile the different theoretical frameworks for understanding the Pacific response to increased CO_2 within state-of-the-art coupled GCMs (Global Climate Models). However, the test of whether the tropical Pacific has become more El Niño- or more La Niña-like is in the hands of the observationalists, and the consequences for our understanding of the climate in the tropical Pacific and in all the regions affected by El Niño/La Niña are great”. At present, the IPCC (2007) has concluded that there is no consistent indication from model simulations regarding how ENSO frequency and amplitude may change. In this regard we note that, off British Columbia, changes in storm tracks associated with La Niña (more westerly) versus El Niño (more southwesterly) have different impacts on inshore sea levels. Relative sea levels are higher on the west coast during La Niña events but higher within the Strait of Georgia during El Niño events (W.J. Crawford, pers. Comm., 2008).

5.0. EXTREME EVENTS AND SEA LEVEL

5.1. OBSERVATIONS OF EXTREME EVENTS FOR THE COASTS OF BRITISH COLUMBIA, WASHINGTON AND OREGON

Extreme sea level events in British Columbia have occurred mainly during El Niño years when monthly mean sea levels are already elevated by several tens of centimeters above background levels (Abeysirigunawardena et al., 2008a,, 2008b; Abeysirigunawardena and Walker, 2008; Tinis, 2008). On December 16, 1982, for example, observed sea levels at Point Atkinson (near Vancouver) reached 5.61 m above chart datum, the highest on record (Tinis, 2008). This event was due to a combination of high winds and very low pressures during a strong El Niño year. The associated storm surges caused significant flooding damage in Boundary Bay, Mud Bay and on Westham Island around the southern Fraser Delta. The highest surge (1.10 m) occurred between 2 and 3 hours before predicted high tide. The highest predicted astronomical tide is 4.59 m; thus, had the storm surge coincided with highest high tide, the water level would have reached about 5.7 m. The mean wind speed at Vancouver International Airport was 30 to 50 km/h from the south-southeast, with gusts reported to 95 km/h; atmospheric pressure reached a low of 98.39 KPa. It was estimated that the sea surface height anomaly associated with the strong El Niño of 1982-83 was 0.20 m (Abeysirigunawardena, 2008b); at Newport, Oregon, this anomaly was estimated at 0.32 m above monthly mean water level and up to 0.19 m above the maximum monthly mean sea level (Komar, 1992; Canning, 2001). None of these estimates takes into account wave run-up into coastal areas which can result in significantly higher elevations being reached by sea water surges (Longuet-Higgins and Stewart, 1962).

Abeysirigunawardena et al. (2008a) estimates that under stable climatic conditions (based on 50 years of historical data) a 5.60 m above chart datum (5.534 to 5.794 m, 95 % confidence interval) sea level event has a return period of about 100 years. For a return period of 200 years, the event would be 5.63 m above chart datum (5.56-5.82 m, 95 % confidence interval). The highest predicted astronomical tides for the region are 4.59 m, as noted above.

During the major1997-98 El Niño, monthly mean sea levels along the Washington coast were 0.40 m above the monthly mean sea level and up to 0.22 m above the maximum monthly mean sea level (Kaminsky et al., 1998; Canning, 2001). Two significant wind wave events occurred along the Washington coast during this season, both on high tides, resulting in serious coastal erosion and inundation. On January 1-2, 1998, high water levels were 0.10 to 0.15 m above predicted high tides and 0.33 to 0.40 m above predicted low tides. Local shoreline retreat of up to 15 m was recorded at Point Brown, Ocean Shores, Washington. On January 17, 1998, the Grays Harbor wave gauge recorded a significant wave height of 14.52 m and a significant wave period of 22 seconds. For six hours prior to the event, significant wave heights were 7.0 m with 20-second periods; significant wave heights remained between 7.4 and 8.5 m for 5 hours after the peak (Canning, 2001).

Walker (2007) shows that the trend in maximum sea levels for Haida Gwaii has been an annual increase of 3.4 mm/year, or twice the rate for the computed mean global sea level of 1.6-1.7 mm/year. He suggests that this may be related to greater storminess associated with major ENSO events. Walker (2007) also cites Graham and Diaz (2001) who conclude that storm intensities in the North Pacific have increased during the period 1940-1998. Unpublished data from D. Abeysirigunawardena show that storm surge-related winds (S-SE; > 50 km/h) have very clearly increased in frequency since the 1976 PDO regime shift (Miller et al., 1994; Walker, 2007). This timing also coincides with the mid-1970s ENSO regime shift (e.g., Trenberth, 2002).

An example of an extreme event in northern British Columbia is the December 23-24, 2003 storm surge which reached a maximum sea level elevation of 8.06 m above chart datum (mean sea level is 3.87 m and the predicted large spring tide was 7.54 m) (Harper, 2004; Walker, 2007; Abeysirigunawardena and Walker, 2008; Tinis, 2008). This storm was accompanied by intense S-SE winds, gusting to 111 km/h and which over a period of 33 hours, created a maximum surge of 0.73 m at Queen Charlotte City. The peak surge fortunately occurred on a low tide making the event less destructive than had it coincided with a high tide. This extreme event was computed to have a probability of occurrence of 1 % in any given year (i.e., return period of 100 years). If the trend for more frequent and more intense extreme events continues, coupled with rising global mean sea levels, the probability of having devastating storm surges coinciding with high tidal elevations will also increase.

5.2. PREDICTED EXTREME EVENT FREQUENCY AND MAGNITUDE

El Niño/La Niña events along the west coast of North America give rise not only to above-average sea levels (see above) but also to more extreme weather conditions such as the storms and related storm surges reported in Section 5.1. Bromirski and Flick (2003) studied long (greater than 50 years) tide gauge records from California to Alaska for storm-forced extreme sea levels. They found no trend over the period of their investigation with respect to the frequency or magnitude of winter extreme sea levels. They suggest that there is a greater influence of El Niño events on winter storm-related extreme sea levels in the southern coastal regions and of La Niña events in the northern coastal regions. Similarly, Abeysirigunawardena et al. (2008b) conclude that British Columbia lies in a transition zone with respect to wind regimes such that wind events are more strongly correlated with La Niña years than with El Niño years. This would appear to be the inverse of that seen farther south along the western North American coast (e.g., Canning, 2001; Trenberth, 2002). While this inverse relationship between extreme wind events and El Niño intervals may exist, Abeysirigunawardena et al. (2008b) suggest that weather variability is such that sufficiently extreme events during El Niño years, coupled with much higher regional steric sea levels, can result in significant inundation and coastal damage. They counsel planners to adopt a precautionary approach by applying extreme recurrences for both winds and water levels in setting scenarios for mitigation and adaptation. For Haida Gwaii, El Niño conditions, through a change in the jet stream path and an associated stronger Aleutian Low in winter, result in wetter weather in general and more storms (Walker, 2007).

With respect to future extreme sea levels, a critical question is "Will ENSO events become more frequent with changing global climatic conditions and will extreme events also increase in frequency along the British Columbia coast?" (see also our earlier discussion for the Tropical Pacific). There are too few data and analyses available at present to answer confidently this important question but there are well-respected researchers who are firmly of the opinion that ENSO events become more frequent, and/or possibly of greater intensity, as global temperatures rise. Trenberth (2002) states that in 1976-77 there was a major change in the evolution of the various manifestations of El Niño throughout its life cycle (wind, temperature, atmospheric circulation, cloud cover, radiation, precipitation, storminess, movement of heat and energy, exchanges of heat and moisture with the surface). This has since become known as the 1976-77 climate shift and is well-recognized by other researchers. The work of his group has since shown an apparent relationship between El Niño events and global warming, though he admits that present climate models do not yet simulate El Niño well enough to enable reliable projections. The current underlying hypothesis is that "El Niño exists and plays a role in the Pacific Ocean as a means of removing heat from equatorial regions of the ocean, where it would otherwise build up. An implication of this, if correct, is that further heat buildup from increasing greenhouse gases in the atmosphere would lead to increased magnitudes and/or frequency of El Niño events" (Trenberth, 2002).Thus, if future analysis of the relationship between El Niño and global climate change supports the linkage between climate change and frequency and magnitude of El Niño events, it is expected that extreme events, such as the storm surges described above, will become more frequent in southern British Columbia simply through the coincidence of extreme weather events and more common higher regional sea levels.

Abeysirigunawardena et al. (2008a) have attempted a preliminary assessment of the effects of global sea level rise and climatic effects on extreme sea levels in southern British Columbia based on two global sea level rise scenarios of 2.8 mm/year and 5.7 mm/year from Church (2002). Table 4 shows the range of extreme sea levels *relative to Chart Datum in 2000* for 100-year and 200-year return periods, assuming no climate change factors on storm frequency, for 2050 and 2100. The two scenarios are shown along with the anticipated 0.34-m rise predicted for Washington State's "Medium SLR Scenario" (Mote et al., 2008; see above). These data are presented in this manner in order to be able to compare *present* actual elevations of coastal structures (e.g., dikes) to the heights of possible extreme sea level events in the future. Such predicted values clearly also assume no absolute changes in land elevation due to geodynamics or subsidence; on the Fraser Delta the amplitudes in 2050 and 2100 would be increased, based on the anticipated annual rate of deltaic subsidence (1-2 mm/year). Thus, the application of deltaic subsidence would have the effect of moving the tabulated 3.4 mm/year sea level rise scenario (Table 4) into the realm of the 5.7 mm/year scenario for the Fraser Delta.

The current elevation for most of the sea dike system in the Fraser River delta region is 6.64 m above chart datum (Abeysirigunawardena et al., 2008a). While the highest values in Table 4 are about 6.38 m for a 200-year return event, it must be remembered that these values do not take into account run-up associated with storm surges or possible climatic impacts on maximum sea level arising from such events. Abeysirigunawardena et al. (2008a) suggest that under some possible climate scenarios affecting the frequency and magnitude of such events, extreme heights of 6.74 m could be achieved. The impact of possible increases in wind wave heights in coastal waters also needs to be considered. In a study of the effects of El Niño-Southern Oscillation (ENSO) on peak wind gusts over the contiguous United States from 1948 to 1998, Enloe et al. (2004) find that the Pacific Northwest experiences a significant increase in wind gustiness during the ENSO cold phase wintertime period from November to March. The warm phase of ENSO is associated with an overall decrease in gustiness in the Pacific Northwest for these months. Thus, we can expect higher amplitude wind waves in coastal regions during November to March during the cold phase of a major ENSO event.

Sea Level Rise Rate (mm/y)	2050 100 year Event (m)	2100 100-year Event (m)	2050 200 Year Event (m)	2100 200-Year Event (m)
2.8	5.67-5.93	5.81-6.07	5.69-5.95	5.83-6.09
5.7	5.81-6.07	6.10-6.36	5.84-6.10	6.12-6.38
3.4	5.70-5.96	5.87-6.13	5.72-5.98	5.89-6.15

Table 4. Extreme event heights (Point Atkinson) *relative to Chart Datum in 2000* for various scenarios of rate of sea level rise and for 100- and 200-year return period events in 2050 and 2100 (based on data in Abeysirigunawardena et al., 2008a). These predictions do not account for any changes in frequency or amplitude effects (ENSO-related) or other steric or estuarine flow reversal effects which might be climate related.

6.0. CONCLUSIONS

1. Based on land elevation time series from Global Positioning System (GPS) sites and water level time series from coastal tide gauges, Absolute Sea Level (ASL) in British Columbia waters rose during the 20th Century at a mean rate (plus standard error) of 1.8±0.2 mm/year, with a standard deviation about the mean of 1.2 mm/year (Mazzotti et al., 2008b). Superimposed on the long-term trend were large amplitude, decadal scale variations in sea level associated with El Niño-Southern Oscillation (ENSO) events in the Pacific Ocean. So large were these variations for the active ENSO period from 1993 to 2003, the ASL for the southern British Columbia region temporarily fell at a rate of -4.4±0.5 mm/year (consistent with consistent satellite altimetry data for this region) before returning to a positive upward trend.

The mean observed ASL for British Columbia is in agreement with the mean 20th Century estimates of global eustatic sea level rise of between 1.5 and 2.0 mm/year derived from tide gauge data. The results are also consistent with the IPCC (2007) reported observed global estimates of 1.8±0.5 mm/year for the period 1961 to 2003.

2. Future relative sea level changes will vary widely in southern British Columbia largely as a result of geodynamic processes of subsidence in the Fraser Delta region and uplift on Vancouver Island (Table 5). A summary of projected sea level changes for many British Columbia sites is presented in Appendix A, Table A1.

3. Steric sea level changes associated with rising ocean temperatures due to global warming are estimated to account for nearly 50% of the observed rate of global sea level rise in the World Ocean (IPCC, 2007). In British Columbia coastal waters, this effect is further exacerbated by regional thermosteric and halosteric effects. In the Strait of Georgia, the halosteric (salinity) effect accounts for approximately 63% of the observed trend in *total steric* sea level rise of 1.2±0.2 mm/year over the past 30 years while thermal heating effects account for the remaining 37%. In offshore regions, thermal and salinity effects contribute more equally to the total steric height change of around 1 mm/year.

If the present halosteric rise of roughly 0.8±0.2 mm/year for the Strait of Georgia (63% of the total steric change) is added to the estimated eustatic rate of 1.8±0.2 mm/year (which incorporates much of the thermosteric contribution also observed in the Strait of Georgia), we estimate a net rate of roughly 2.6 mm/year for the strait. Projecting this rate into the future (and ignoring accelerated sea level rise due to enhanced glacial melt, temperature rise, and the reduction in water impoundment in the world's artificial reservoirs), we find that relative sea levels in the Strait of Georgia would, in the absence of land movement, increase by roughly 24 cm by these effects alone by 2100. This effect may be mitigated by uplift of the land in the shores adjacent to the strait or enhanced by subsidence of the sediments in the Fraser River delta region.

4. Because of continuing Glacial Isostatic Adjustment (GIA), regional tectonic processes and local oceanic processes, relative sea level change can differ markedly from Absolute Sea Level change. This is particularly true of the tectonically active region of western British Columbia where variations in land elevation relative to the earth's center of mass can lead to pronounced differences in the direction and magnitude of relative sea level change over scales of tens of kilometers (see Appendix A for details).

Based on existing tide gauge records and adjustment for accelerated global sea level rise over the next century, we find that by 2100 relative sea levels in major BC coastal regions are expected to vary significantly from region to region. Assuming a eustatic sea level rise of 30 cm by 2100 (the mean estimate from IPCC 2007), relative sea level at Prince Rupert will have increased by about 25 cm with a range of uncertainty from 13 to 37 cm. Similarly, for Point Atkinson and Vancouver the mean projected rises are 18 and 19 cm with ranges of 6 to 30 cm and 8 to 32 cm, respectively. For Victoria, results yield a mean sea level rise of 19 cm with an estimate range 7 to 31 cm. In contrast, relative sea level in Tofino will only rise by roughly 5 cm (range of -8 to 18 cm) due to the countering effect of tectonic uplift on outer coast, while relative sea level in Delta and New Westminster will likely rise by around 50 cm (range 32 to 68 cm) due to sediment compaction and water loss.

5. The current dike elevation for most of the dike system in the Fraser River delta region is 6.64 m above current chart datum. While the highest predicted water elevations due to storm surges are about 6.38 m for a 200-year return event, these values do not take into account run-up associated with storm surges and wind waves, nor any possible climatic impacts on maximum sea level associated with such events (cf. the discussion on wind gusts associated with the cold and warm phases of ENSO at the end of section 5). Under some possible climate scenarios affecting the frequency and magnitude of such events, extreme heights of 6.74 m could be achieved. An analysis of storm surge events recorded at the Point Atkinson tide gauge over the past 45 years (supported by numerical simulations using a high resolution Princeton Ocean Model storm surge model) indicate that mid-winter storm surges in excess of 1 m above chart datum (adjusted for regional long-term sea level rise) are likely during the 21st Century.

Source	**Mean (cm)**	**Lowest (cm)**	**Highest (cm)**
Long-term trends			
Global eustatic×93 years + 13(±11)	29.7	18.7	40.7
Halosteric effect (Strait of Georgia waters)	7.6	6.3	8.8
Halosteric effect (Northeast Pacific waters)	3.4	2.8	4.0
Vertical Land Motion (Strait of Georgia region)			
Tectonic contribution @ 0.0±0.5mm/year	0	-4.7	4.7
GIA contribution @ -0.25±0.05 mm/year	-2.3	-1.9	-2.8
Subsidence (Fraser Delta only) @ +3.0±0.7 mm/year	27.9	21.4	34.4
Vertical Land Motion (West Coast Van. Is.)			
Tectonic contribution @ -3.0±0.5 mm/year	-27.9	-23.3	-32.6
GIA contribution @ -0.15±0.05 mm/year	-1.4	-0.9	-1.9
Total (Strait of Georgia)	35.0	18.4	51.4
Total (Fraser River Delta)	55.3	33.4	77.0
Total (West Coast Vancouver Island)	3.8	-2.7	10.2
Amplitudes of fluctuations about trend			
Seasonal steric height	15	10	20
Seasonal atmospheric pressure	15	5	50
Seasonal winds and currents	15	10	25
Storm surges	40	10	100
Major ENSO steric height	50	30	100
Major ENSO atmospheric pressure	10	0	30

Table 5. Summary of anticipated contributions (cm) to relative sea level change by 2100 for coastal British Columbia, with specific focus on the Strait of Georgia (see Appendix A for method of calculation). Only the regional halosteric contributions are included in the steric terms since the eustatic rise predicted by IPCC (2007) already takes into account the effect of ocean warming. The halosteric contribution for the northeast Pacific is derived using Thomson and Tabata (1989) and is 33% of the total steric height rise of 1.1±0.2 mm/year for the period 1956-1986. A positive value indicates that the particular contribution will cause relative sea level to rise; a negative value means that it will cause sea level to fall.

6. Land elevations on the west coast of SW Vancouver Island and Olympic Peninsula are rising (and corresponding relative sea levels falling) due to tectonic processes but will drop by approximately 1 m within minutes when the next megathrust (magnitude ~9) earthquake occurs on the Cascadia Subduction Zone.

7. Hydrological studies during the 20th Century show that there has been a shift towards earlier snowmelt and higher discharges in the spring for British Columbia rivers, including the Fraser and Skeena. The analysis suggests that, under climate change scenarios, flows in northern and southern rivers would increase in the spring and have earlier freshets. Northern rivers would undergo slight increases in flow during summer whereas southern rivers would experience decreases in summer flow. Changes in the timing of river discharges would alter the timing of the annual and semiannual peaks in the steric contributions to the relative sea level rise in coastal waters.

8. The test of whether the tropical Pacific has become more El Niño- or more La Niña-like is in the hands of the observationalists, and the consequences for our understanding of the climate in the tropical Pacific and in all the regions affected by El Niño/La Niña are great.

7.0. PROJECTED SEA LEVEL RISE IN BRITISH COLUMBIA – SUGGESTED RESEARCH

1. *Global glacier and ice cap contributions to eustatic sea levels.* The long-term significance of fresh water contributions to the world ocean from continental and mountain glaciers remains one of the greatest uncertainties in predicting eustatic mean sea level rise through the 21st Century. This deficiency is well-recognized by the scientific community and proposals for further work have been developed to improve measurement, monitoring and modeling capabilities to better refine projections. Many of these will involve filtering and re-analysis of satellite altimetry and gravity data and development of new more precise approaches to monitoring retreat rates of mountain glaciers. Most work, to date, has understandably been focused on the large Greenland and Antarctic ice sheets; more attention is required to further understand the contributions of mountain glaciers around the globe.

2. *Coupling of regional sea level change to climate-scale changes in ocean circulation and steric effects.* The atmospheric and oceanic circulation systems are complexly coupled through complex feedback mechanisms. Long-term repositioning of the basin-scale North Pacific High and Aleutian Low atmospheric pressure systems in the North Pacific could conceivably give rise to long-term changes in sea level associated with the corresponding changes in the dynamical contributions from oceanic wind regimes and circulation. Repositioning of these permanent pressure cells would also effect steric sea level changes arising from changes in vertical mixing, horizontal advection and upwelling. Changes in the atmospheric regimes might also be accompanied by changes in wind intensity and the paths of storm tracks. Modeling is required, on a regional scale, to better understand possible scenarios in the northeast Pacific for atmospheric/oceanic circulation in relation to anticipated global climate change, and the implications for sea level elevations at the coast (mean, seasonal and extreme events).

3. *Hydrologic modeling of coastal British Columbia watersheds.* The volume of freshwater entering coastal waters of British Columbia will have an impact on coastal circulation and, through dynamic and steric effects, sea levels. While limited modeling of Fraser River fluvial regime under climate change exists, there has been little focus on other watersheds. As regional climate modeling improves, research is required to focus particularly on: (a) rivers entering the central and North Coast of British Columbia (especially the Skeena River); (b) glacier-fed coastal rivers which are primarily located on the British Columbia mainland; and, (c) rainfall-dominated watersheds mainly on Vancouver Island. It will be important to understand the nature of regime shifts from glacier-dominated to rainfall-dominated systems and the possible redistribution of these flows throughout the year.

4. *Storm surge frequency and magnitude.* As global sea level continues to rise, there will be an increasing impact of storm surges on the low lying regions of British Columbia. Further research and numerical modeling is needed to improve the forecast and predictions of storm surges in British Columbia, including changes in frequency, intensity and direction of future major storm events.

5. *ENSO frequency and magnitude.* As observed from tide gauges and satellite altimetry in the Pacific, there is a clear relationship between El Niño events and sea level. Major El Niño events also lead to anomalously high sea levels along the coast of British Columbia. We can anticipate a likely relationship between these equatorial events and extreme water levels on the British Columbia coast, although they appear to be less well correlated than for areas farther south along the west coast of North America. Present coupled atmosphere/ocean models are beginning to deal with ENSO phenomena but are not yet particularly sophisticated. It will be important to understand whether global climate change in the tropical Pacific will be El Niño- or La Niña-like and, if El Niño-like, how it will affect the frequency and magnitude of ENSO events on coast of British Columbia. Changes in these events will, in turn, have implications for mean regional sea levels and the frequency and amplitudes of extreme sea levels associated with storms.

6. *Steric effects in the North Pacific and coastal waters.* According the latest IPCC (2007) report, steric contributions rival the contributions from melting ice on long-term increases in global sea level. Determining the future rate of change of sea level from increased global heating and the

advective redistribution of heat and salt in the ocean presently lies with a determination of steric sea level changes from oceanic temperature-salinity profile observations collected during the late 20th Century and early 21st Century (e.g., Thomson and Tabata, 1987, 1989). Projected estimates will continue to improve with ever expanding time series of oceanic CTD profile data provided by repeat shipboard survey lines (the La Perouse Project of Fisheries and Oceans Canada), moored buoy instrumentation, cabled observatory instrumentation (NEPTUNE Canada), and the International Argo (drifting 1000 m profiling float) program. Eventually, coupled ocean-atmosphere GCMs, with realistic ocean circulation and surface mixing dynamics will be capable of determining the contributions of halosteric and thermosteric effects on global and regional sea level rise.

7. *Need for long term measurements by tide gauges, GPS and CTD profiling (for steric effects).* A key to successful climate change data analysis and numerical modeling is the availability of reliable long-term measurements. Governments therefore need to continue funding support for ongoing time series measurements (including tide gauge, GPS, meteorological, and CTD programs) and initiate new tide series for poorly sampled coastal regions and highly vulnerable shorelines. In particular, the CTD profiling series at the Nanoose Bay site as well as on the west coast of Vancouver Island and at Station “P” need to be maintained and upgraded.

ACKNOWLEDGEMENTS

This report would not have been researched and written without the encouragement and financial support provided by Ben Kangasniemi of the Climate Change Branch of the British Columbia Ministry of Environment. Ben's guidance and insight throughout this work have been greatly appreciated. We thank Neil Peters, the BC Inspector of Dikes, for his generous support for the project as well as Hugh Fraser and Paula Kolisnek of the Corporation of Delta for their ongoing enthusiasm for the Storm Surge modeling work. Many of the results presented in the report were made possible through the expert data processing and analysis contributed by Casey Jones, Alexander Rabinovich, Roy Hourston, and Jane Eert. Sheri Ward expertly helped reformat the text for publication. The support of Natural Resources Canada (through the "Enhancing Resilience in a Changing Climate" program) and the Oceans Science Division of the Department of Fisheries and Oceans is also gratefully acknowledged. Acquisition and analysis of GPS data were supported by the Canadian Crustal Deformation Service (Natural Resources Canada).

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APPENDIX A: CALCULATION OF RELATIVE SEA LEVEL (RSL) CHANGE BY YEAR 2100

Relative sea level change by the year 2100 can be estimated by the formula

$$RSL_{2100} = (V_{ocean} - V_{land}) \times (2100\text{-Year}) + IPCC_{adjust} \qquad \text{(A.1a)}$$

$$= V_{RSL} \times (2100\text{-Year}) + IPCC_{adjust} \qquad \text{(A.1b)}$$

where V_{ocean} and V_{land} are the time varying rates of *absolute* sea level (in mm/year) due to processes in the ocean and the land, respectively, as measured relative to the Earth's center of mass, and $V_{RSL} = (V_{ocean} - V_{land})$ is the known rate of relative sea level rise measured at a given coastal site. Both V_{ocean} and V_{land} are positive when directed vertically upward so that land uplift represents a positive rate whereas land subsidence a negative rate (and therefore adds to the ocean effect).

The IPCC (2007) Adjustment ($IPCC_{adjust}$) accounts for the fact that the change in global sea level over the next hundred years is unlikely to be a linear trend but will accelerate with time. This factor is calculated using data in the IPCC 2007 report and the findings of Mazzotti et al. (2008b). Specifically, Mazzotti et al. (2008b) and IPCC (2007) find that the present eustatic rate of sea level rise is 1.8±0.2 mm/year which, assuming that the present linear trend continues from 2007 over the next hundred years, should lead to a net rise in sea level of 1.8±0.2 mm/year × 93 years = 16.7 ±1.9 cm by 2100. However, IPCC (2007) predicts a total change for the world ocean of 30 cm by 2100 with range from 19 to 42 cm. Thus, we need to "correct" (adjust) any calculation based on the present linear trend by the following amount: $IPCC_{adjust}$ = 30.0-16.7 cm = 13.3 cm with a range of 2.3 to 25.3 cm. This becomes approximately,

$$IPCC_{adjust} \cong 13 \pm 11 \text{ cm.} \qquad \text{(A.2)}$$

When we combine (A.2) with (A.1), we find

$$RSL_{2100} = V_{RSL} \times (2100\text{-Year}) + 13\ (\pm 11) \text{ cm} \qquad \text{(A.3)}$$

For changes in Relative Sea Level measured relative to the year 2007, the formula becomes

$$RSL_{2100} = V_{RSL}(2007) \times 93 \text{ years} + 13\ (\pm 11) \text{ cm} \qquad \text{(A.4)}$$

where $V_{RSL} = (V_{ocean} - V_{land})$ is measured in mm/year.

Tide Gauge				Relative Sea Level			RSL by 2100		
Site	**Lat.**	**Long.**	**T**	**V_{RSL}**	**σ**	**RMS**	**RSL_{2100}**	**Range**	**Cat.**
	(°N)	(°E)	(yr)	(mm/yr)		(mm)		(cm)	
Prince Rupert	54.317	-130.324	77	1.3	0.1	18	25.1	13.2, 37.0	C
Q Char City	53.252	-132.072	45	-0.4	0.2	23	9.3	-3.6, 22.1	C
Bella Bella	52.163	-128.143	45	-0.5	0.3	22	8.4	-5.4, 22.1	C
Winter Harb	50.513	-128.029	18	0.1	0.8	23	13.9	-4.5, 32.4	F
Zebellos	49.979	-126.846	13	-3.3	1.6	19	-17.7	-43.6, 8.2	F
Gold River	49.679	-126.126	13	1.1	1.8	25	23.2	-4.5, 51.0	F
Tofino	49.154	-125.913	58	-0.9	0.2	22	4.6	-8.2, 17.5	B
Port Alberni	49.233	-124.814	40	-0.7	0.6	27	6.5	-10.1, 23.1	B
Bamfield	48.836	-125.136	37	0.2	0.3	14	14.9	1.1, 28.7	B
Port Renfrew	48.555	-124.421	27	2.2	0.6	43	33.5	16.9, 50.0	C
Port Hardy	50.722	-127.489	43	-0.7	0.3	20	6.5	-7.3, 20.3	B
Alert Bay	50.587	-126.931	33	-1.7	0.4	27	-2.8	-17.5, 11.9	B
Campbell R'vr	50.042	-125.247	37	-2.3	0.5	17	-8.4	-24.0, 7.3	F
Little River	49.741	-124.923	25	-1.2	0.6	20	1.8	-14.7, 18.4	C
Pt. Atkinson	49.337	-123.253	73	0.5	0.1	18	17.7	5.7, 29.6	B
Vancouver	49.287	-123.110	58	0.6	0.1	13	18.6	6.7, 30.5	B
New West	49.200	-122.910	38	-2.8	2.0	133	-13.0	-42.6, 16.6	F
Fulford Harb	48.769	-123.451	40	0.4	0.1	10	16.7	4.8, 28.7	B
Patricia Bay	48.654	-123.452	31	0.1	0.8	14	13.9	-4.5, 32.4	B
Victoria	48.424	-123.371	98	0.6	0.1	16	18.6	6.7, 30.5	A
Sooke	48.370	-123.726	12	-1.5	0.9	15	-0.9	-20.3, 18.4	F
Cherry Point	48.863	-122.758	34	0.5	0.2	11	17.7	4.8, 30.5	B
Friday Harb	48.547	-123.010	73	0.9	0.1	10	21.4	9.4, 33.3	A
Seattle	47.605	-122.338	107	2.2	0.1	14	33.5	21.5, 45.4	A
Tacoma	47.267	-122.413	10	1.9	1.2	14	30.7	8.5, 52.8	F
Port Townsend	48.112	-122.758	35	1.9	0.2	11	30.7	17.8, 43.5	B
Port Angeles	48.125	-123.440	32	-0.1	0.2	13	12.1	-0.8, 24.9	F
Neah Bay	48.368	-124.617	47	-2.1	0.2	16	-6.5	-19.4, 6.3	B
MEAN				**-0.13**	**1.48**		**11.8**	**-4.1, 27.6**	

Table A.1. Relative sea level height RSL_{2100} by 2100 relative to 2007 based on tide gauge records. Range = (VRSL±σ)×93 years+ 13(±11) cm and uses extremes from the estimates. Adapted from Mazzotti et al. (2008b). T = Equivalent time (in years) of complete data coverage (i.e., time span minus data gap periods); V_{RSL} = present upward velocity of relative sea level; σ = standard error of the estimate; RMS = root-mean-square deviation; RSL_{2100} = predicted relative sea level change by 2100; Cat. = Combined tide gauge-GPS category ranking in which A denotes the most reliable estimate and F a non-reliable estimate.

Location	Method	Q	RSL_{2100}		
			Mean (cm)	**5% CI** (cm)	**95% CI** (cm)
Prince Rupert	TG	2	25	13	37
	GPS	0	46	18	75
Nanaimo	GPS	3	11	-6	28
Victoria	TG	3	19	7	31
	GPS	3	17	1	34
Vancouver	GPS	2	33	14	52
	TG	2	19	7	31
Fraser River Delta	GPS / InSAR	2	50	32	68
Port Angeles	TG	1	12	0	25
Seattle	TG	3	34	22	46
	GPS	3	39	24	53
Tacoma	TG	1	31	9	53
	GPS	3	33	14	52

(a) Predicted relative sea level rise by 2100 based on the *mean* estimate of global eustatic sea level increase of 30 cm by IPCC (2007).

Location	Method	Q	RSL_{2100}		
			Mean (cm)	**5% CI** (cm)	**95% CI** (cm)
Prince Rupert	TG	2	95	65	125
	GPS	0	116	76	155
Nanaimo	GPS	3	80	48	113
Victoria	TG	3	89	58	119
	GPS	3	94	63	126
Vancouver	GPS	2	103	69	136
	TG	2	89	58	119
Fraser River Delta	GPS / InSAR	2	120	87	153
Port Angeles	TG	1	82	52	112
Seattle	TG	3	103	73	134
	GPS	3	108	77	140
Tacoma	TG	1	101	65	16
	GPS	3	103	69	136

(b) As in (a) but for the *extreme* predicted eustatic increase by 2100 of 100 cm.

Table A2. Relative sea level height RSL_{2100} by 2100 at major coastal urban centers for mean and extreme predictions of global sea level rise (after Mazzotti et al., 2008b)**.** Tech. = Technique used for vertical motion estimation. Q = Quality of the estimated RSL from 0 (lowest) to 3 (highest). RSL mean, 5%, and 95% levels = Relative sea level rise (positive) or fall (negative) as mean and 90% confidence interval (5% to 95% values).