Estimating Sea-level Allowances for Atlantic Canada under Conditions of Uncertain Sea-Level Rise

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by

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ABSTRACT

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This report documents the methodology of computing sea-level rise allowances for Atlantic Canada in the 21st century under uncertain sea-level rise. The allowances (Hunter 2012) are defined as the amount by which an asset needs to be raised in order to maintain the same likelihood of future flooding events as that site has experienced in the recent past. The allowances are determined by the combination of the statistics of present tides and storm surges (storm tides) and the regional projections of sea-level rise and associated uncertainty (Hunter et al., 2013). Tide-gauge data for nine pilot sites from the Canadian Atlantic coast are used to derive the scale parameters of present sea-level extremes using the Gumbel distribution function. The allowances in the 21st century, with respect to the year 1990, were computed at 10-year intervals for the Intergovernmental Panel on Climate Change (IPCC) A1FI emission scenario. For Atlantic Canada, the allowances are regionally variable and for the period 1990-2050, range between -13 and 38 cm while, for period 1990-2100, they range between 7 and 108 cm. The negative allowances in the Gulf of St. Lawrence are caused by land uplift due to glacial isostatic adjustment (GIA).

RÉSUMÉ

Le présent rapport contient la méthodologie utilisée pour calculer les tolérances relatives à l'élévation du niveau de la mer pour le Canada atlantique au XXIe siècle en cas d'élévation incertaine du niveau de la mer. Les tolérances (Hunter 2012) sont définies comme étant le niveau auquel un actif doit se trouver pour maintenir la même probabilité d'inondations futures que celles que l'emplacement a connues récemment. Les tolérances sont déterminées grâce à la combinaison des statistiques relatives aux marées actuelles et aux ondes de tempête (marées de tempête) et des prévisions régionales de l'élévation du niveau de la mer, ainsi que de l'incertitude qui y est associée (Hunter et al., 2013). Les données provenant des marégraphes de neuf emplacements pilotes sur la côte atlantique canadienne sont utilisées pour déterminer les paramètres d'échelle d'extrêmes des niveaux de la mer actuels à l'aide de la fonction de distribution de Gumbel. Au XXIe siècle, les tolérances, par rapport à l'année 1990, étaient calculées à dix ans d'intervalle pour le scénario d'émissions A1F1 du Groupe d'experts intergouvernemental sur l'évolution du climat. Pour le Canada atlantique, les tolérances varient selon les régions. Elles s'établissaient entre -13 et 38 cm pour la période allant de 1990 à 2050 et entre 7 et 108 cm pour la période allant de 1900 à 2100. Les tolérances négatives dans le golfe du Saint-Laurent sont causées par un soulèvement des terres en raison d'un ajustement isostatique glaciaire.

1. Introduction

The selection of flood levels for adaptation planning requires an understanding of present and future sea-level rise (SLR), vertical land motion, extreme water levels (combined tide and surge), harbour seiche and wave runup (Forbes et al., 2009). One of the difficulties in estimating future extreme water levels is the large uncertainty associated with the estimate of SLR. In 2012, Fisheries and Oceans Canada (DFO) funded a one-year pilot project under the Aquatic Climate Change Adaptation Services Program (ACCASP) to implement methodologies for estimating extreme sea levels and their associated uncertainties arising from a variety of climate change influences. These methodologies primarily focused on the lower-frequency ocean variables, such as changes in mean sea level.

For this project entitled Pilot Tools for Estimating Waves and Sea-Level Extremes under Conditions of Uncertain Climate Change, three methods were proposed to study projected future changes in mean sea level and extreme sea-level events and their associated uncertainties. Extreme sea-level events are generated by storm-surges and high tidal levels and will be influenced by future changes to mean sea level. The project provides probabilistic estimates of the extreme highs in total sea level at different future times. The first method is a standard extreme value analysis that determines the future occurrence of extreme-event sea levels based on past observations, but only crudely takes into account changes in mean sea level. The other two methods include the recently published allowance approach (Hunter, 2012; Hunter et al., 2013), and one being developed at Dalhousie University by Dr. Keith Thompson. The two new methods take into account changes in future mean sea-level rise, changes in the magnitude and frequency of extreme events such as surges in the future associated with climate change, and the uncertainties in projections of these changes.

The allowance approach (Hunter, 2012, Hunter et al., 2013) was chosen in consultation with DFO Small Craft Harbours (SCH) and Real Property, Safety and Security (RPSS). It was applied at several representative sites in Atlantic Canada with differing, and compounding sources of sea-level rise. A focus of the approach is to determine the allowances, which is defined as the vertical distance that an asset needs to be raised under a rising sea level, so that the present likelihood of flooding does not increase. The “adaptation tools” from the initial one-year pilot study are graphical displays and tabular summaries of the results of the application of the methodologies to sites such as Halifax, Saint John, Charlottetown and St. John’s where long tide-gauge records provide critical observational constraints and input to the methodologies. The tools are in the form of probabilistic estimates of the return levels associated with different return periods, and of the expected number of exceedances of particular extreme levels at different times, at the test sites. The exceedance represents a flooding event where sea level exceeds a certain height. The exact form of the tool is expressed as the sea-level rise allowances, determined in consultation with client representatives in Atlantic Canada and external sea-level projection experts.

This project will consider both the decadal and 50-year time scales identified by ACCASP, but will focus on the 50-year time scale because of its greater relevance to the design of long-term infrastructure. The new methodologies are particularly important for the 50-year and longer time scales because the amount of sea-level rise is projected to increase with time. As well, over longer time periods there is larger uncertainty. For example, the possibility of amplified global sea-level rise due to accelerated melting of the Greenland and Antarctic ice sheets has been raised. This project has benefited greatly from the outputs of the ACCASP Trends & Projections effort being carried out for the Atlantic Basin.

This report focusses on sites in Atlantic Canada where long tide-gauge records exist. Sea-level rise allowances are computed for each site based on regional projections of sea level. The regional projections incorporate the vertical land motion due to glacial isostatic adjustment (GIA) and sea-level fingerprinting (Hunter et al., 2013), which is the gravitationally driven redistribution of meltwater in the global ocean (James et al., 2011). The allowances will enable SCH and RPSS sectors to carry out infrastructure planning through their normal process, which assumes no change in sea level. The allowance is the elevation increase that would maintain the same level of risk of flooding events that is assumed for their analysis under present conditions. It is important to note that the allowance approach only deals with the effect of SLR on inundation, but not on coastline recession through erosion (Ranasinghe et al., 2012).

This report is structured as follows. Section 2 explains the theory used to compute sea-level allowances. Section 3 summarizes the tide-gauge and GPS measurements. Section 4 describes the statistics of extreme water levels, and Section 5 presents the projections of regional sea-level rise. Sea-level rise allowances are presented in Section 6, followed by conclusions in Section 7 and future steps in Section 8.

2. Theory

Extreme value theory develops techniques and models for describing the unusual rather than usual, such as annual maximum sea levels (Coles, 2001). The model is expressed in the form of extreme value distributions, with type I distributions widely known as the Gumbel family. The Gumbel distribution has proved very useful in analysis of annual maxima of hourly measurements of sea level in the northwest Atlantic (Bernier and Thompson, 2006; Bernier et al., 2007). Some basic statistics may be derived from Gumbel distribution function to describe the likelihood of sea-level extremes, including return period (R) and return level (z), exceedance probability (E), and expected number of exceedances (N) for a given period (T) (Pugh, 1996; Hunter, 2012). The return period is the average period between extreme events (observed over a long period with many events) and the exceedance probability is the probability of at least one exceedance event happening during a given period. These statistics are related by:

$$F = 1 - E = \exp\left(-\frac{T}{R}\right) = \exp(-N) = \exp\left[-\exp\left\{\frac{\mu - z}{\lambda}\right\}\right], \tag{1}$$

In which μ is the location parameter, λ is the scale parameter and F is the cumulative distribution function. Here R is often estimated from the annual exceedance probability using

$$E = 1 - \exp\left(-\frac{1}{R}\right). \tag{2}$$

Sea-level rise (SLR) will modify the likelihood of future sea-level extremes. Because of the uncertainty in the amount of future sea-level rise, the elevation change required to maintain the same likelihood of extreme events is larger than the change in mean sea level (Hunter, 2012). One common adaptation to sea-level rise is to raise the infrastructure by an amount that is sufficient to achieve a required level of precaution. Hunter (2012) describes a simple technique for estimating future allowances by combining the statistics of present extreme sea levels and projections of the rise in mean sea levels and their associated uncertainties. The overall expected number of exceedances, N_{ov}, under sea-level rise is given by

$$N_{ov} = Nexp[\frac{\Delta z + \frac{\sigma^2}{2\lambda} - a}{\lambda}], \tag{3}$$

where Δz is the central value of the estimated rise, σ is the standard deviation of the uncertainty in the rise and a is the amount by which a coastal asset is raised to allow for sea-level rise. N is the expected number of exceedances in the absence of sea-level rise and with the asset at its original height. The factor by which frequency of flooding events will increase with a relative sea-level rise of Δz is given by $\exp(\frac{\Delta z}{\lambda})$. In order to ensure that the expected number of extreme events in a given period remains the same as it would without sea-level rise, we require that $N_{ov} = N$. Therefore the allowance, a, is given by

$$a = \Delta z + \frac{\sigma^2}{2\lambda}. \tag{4}$$

In other words, if the infrastructure is raised by an amount a, the future flooding risk will remain the same as the present-day flooding risk. The allowance approach does not take into account possible changes in the frequency and intensity of variability about mean sea level, such as storminess. This will be dealt with in a new approach currently under development by Dr. Keith Thompson of Dalhousie University.

3. Summary of tide-gauge data and GPS records

The hourly water level data for nine tide-gauge stations were downloaded from the AZMP websites (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/sl-pm/index-eng.asp). The tide gauges measure sea level relative to land. The zero water levels at tide gauges are the local Canadian Hydrographic Service Chart Datum. The data were used to develop the sea-level adaptation tools for Atlantic Canada. These stations (Figure 1) have records of water levels longer than 25 years, which is needed for a satisfactory extremal analysis (Pugh, 1996). The tide-gauge data are very useful for understanding present SLR and statistics of extreme water levels. In particular, the tide gauge stations in Charlottetown, Halifax and Saint John have century-long records of sea-level measurements (Table 1), providing a robust observational underpinning to the methodologies. It should be noted that the tide gauge in Saint John had siltation problems starting in 1980. The gauge was moved in 1999 and modified in 2006 (Greenberg et al., 2012).

The rate of relative SLR at each tide-gauge station is computed using the least-squares fit to annual means of hourly sea-level data for all available years (Table 1). A representative time series of annual means is given for Halifax in Figure 2. The well-defined linear trend (calculated for all available years) is evident, although decadal-scale variability leads to different rates of SLR for different periods (Greenberg et al., 2012; Hebert et al., 2012). The rates of relative SLR show a large-scale spatial structure in Atlantic Canada. For example, the rates along the coasts of Nova Scotia and PEI are between 3.2 ± 0.1 and 3.6 ± 0.4 mm/yr, which are higher than the global averaged rate of 1.9 ± 0.4 mm/yr (Church and White, 2011). The Rimouski tide-gauge data show a much lower rate of 1.3 ± 0.9 mm/yr than the global average rate, and there is no significant sea-level change at Quebec City. The rates of relative SLR in St. John's, Newfoundland, and in Saint John, New Brunswick, have values of about 2 mm/y, similar to the globally averaged rate.

Table 2 summarizes the vertical land motion (uplift or subsidence) at tide-gauge stations based on GPS observations, which are relative to the centre of the Earth. In Atlantic Canada, vertical crustal motion is mainly due to glacial isostatic adjustment (GIA). Two sources of uncertainty associated with the GPS data are the linear regression error (about 0.2 mm/yr) and the uncertainty of the terrestrial reference frame realization (about 0.5 mm/yr). They are added in quadrature (square root of summed squares) to get the final uncertainty. The reference frame errors dominate and nearly all the GPS vertical rates have uncertainties at the 0.5 to 0.6 mm/y level. The GPS data were processed using the Geodetic Survey Division Precise Point Positioning (PPP) software. The rates of the vertical land motion from PPP have been compared to the rates derived from an analysis of the GPS data using the Bernese software (Dach et al., 2007), and they are in good agreement.

We replicated an analysis that was carried out by Mazzotti et al. (2008) for the west coast of Canada in order to show the consistency between tide gauge trends and GPS measurements of vertical crustal motion. In Figure 3, the x-intercept of the line is the average of the sum of tide gauge and GPS rates with the Sept-Iles tide-gauge removed. It represents the rate of relative sea-level change for a situation in which the vertical land motion is zero. The intercept has a value of 2.5 ± 0.9 mm/yr and encompasses the global average sea-level rise of 1.9 ± 0.4 mm/yr since 1961 based on tide-gauge record. This suggests that the x-intercept was a valid measure of eustatic sea-level change, and that GIA effect explains overall spatial pattern of tide-gauge trends in Atlantic Canada.

The budget for the global average sea-level rise since 1970 comprises about 40% from ocean thermal expansion, 40% from melting of glaciers and ice caps, and 20% is due to contributions from Greenland and Antarctica. There is also an offsetting contribution from changes in terrestrial storage (Church et al., 2011). Shepherd et al. (2012) reconciled satellite measurements of ice-sheet mass balance. Since 1992, the polar ice sheets contributed, on average, 0.59 ± 0.20 mm/yr (about 20%) to the rate of global sea-level rise.

4. Statistics of extreme water levels

The method of ranking annual maximum water levels should strictly be applied only to data in which no significant trends occur (Pugh, 1996). This means that the probability of a particular annual maximum is the same at the beginning and end of the data set. Their occurrence therefore follows a Poisson distribution. Prior to doing the extreme analysis, we removed the temporal trend due to changes in mean sea level from the record by subtracting the annual mean from the corresponding annual maximum (henceforth, the adjusted annual maxima). Missing years of data should not affect the validity of the results provided that the gaps are not due to the extreme values themselves, such as an extreme event damaging the recording instrument so that the record of the extreme event is missing. The adjusted annual maxima represent the variability with respect to the mean and show no significant increasing trend (Figure 2, bottom). The adjusted annual maxima were checked such that any extreme events were closer than 3 days were counted as a single event.

The adjusted annual maxima are fitted to a Gumbel distribution using the evfit function in MATLAB. The software estimates the maximum likelihood estimation of the cumulative density function (F), and 95% confidence bounds for F. The standard diagnostic graphic checks (Appendix I) imply that the Gumbel distribution provides a reasonable fit to the observed extremes at all tide gauge locations. Figure 4a shows that the frequency distribution and associated Gumbel fit for Halifax are not symmetrical and have a long tail. The cumulative Gumbel distribution of annual maxima (Figure 4b) indicates the probability of water levels lower than a threshold and agrees reasonably well with the ordered adjusted annual maxima marked by the red dots.

The return-level curve (Figure 5 and Appendix A) indicates the good quality of the Gumbel fit since the data lie within 5% to 95% confidence range, which increases with increasing return period since the data provide increasingly weaker information about higher water levels (Coles, 2001). The curves of exceedance probability for a given period are terminated at the low-probability end of the plot when the water level exceeds 100-year return level. At present, the 50-year return level in Halifax is 172 cm and the probability of the adjusted annual maxima to exceed this level is low (about 2%) for any given year (Equation 1). However for a given period of 50 years (i.e., a typical asset life), the exceedance probability increases to 63%.

The Gumbel model parameters and 50-year return levels for all tide-gauge stations show large spatial variations (Table 3). The location parameter is equal to the 1-year return level, and is largely determined by tide with the smallest parameter of 101.2 cm in North Sydney, and the largest parameter of 428.2 cm in Saint John. The scale parameter depends in a subtle way on both the distribution of tidal heights and the distribution of surge heights. The slope is relatively large in Quebec and Charlottetown where surges are typically largest, whereas the slope is the smallest in St. John’s where tides are relatively small and surges are intermediate (Bernier and Thompson, 2006, Figure 10). The smaller slope indicates that the return period is sensitive to quite small changes in mean sea-level rise, which will be discussed in detail in section 6. For long return periods, the return levels are due to the combined effect of large tides and large surges. The 50-year return level is largest (470 cm) in Saint John, New Brunswick, in the Bay of Fundy where there is large tidal amplitude. It is smallest (141 cm) in St John’s, Newfoundland where both tides and surges are small.

5. Projections of relative sea-level rise

The derivation of the projections of relative sea-level rise in Atlantic Canada followed the methodology of Church et al. (2011) and Slangen et al. (2012), and is described in detail by Hunter et al. (2013, Appendix 1). The resultant projections are composed of terms due to: 1) the global-average sea-level rise which includes contributions due to thermal expansion, melting ice from glaciers and ice caps, Greenland and Antarctic ice sheets, and ‘scaled-up ice sheet discharge’ (Meehl et al., 2007); 2) spatially-varying ‘fingerprints’ to account for changes in the loading of the Earth and in the gravitational field, in response to ongoing changes in land ice

(Mitrovica et al., 2001, 2011); 3) spatially-varying sea-level change due to change in ocean density and dynamics provided by atmosphere-ocean general circulation models (AOGCMS, Meehl et al., 2007); 4) spatially-varying glacial isostatic adjustment (GIA) using the ICE-5G model (Peltier, 2004) and modeling methodologies described by Kendall et al. (2005). GIA is the ongoing response of the Earth (solid surface motion and changes to the Earth's gravitational field) to changes in surface loading caused by past changes in land ice, especially the deglaciation of the continental-scale ice sheets that commenced about 20,000 years ago.

Church et al. (2011) showed that the projected global-average SLR for all SRES scenarios range from 19 to 63 cm for 2100 compared to 1990. When including dynamic changes in the ice sheets, the total range at 2100 is 18-80 cm. SLR derived from tide gauges and satellite measurements since 1990 are close to the top of the model projections summarized in the 2001 assessment report of the IPCC, suggesting that IPCC projections have not exaggerated but may even have underestimated the change in sea level (Rahmstorf et al., 2007; Rahmstorf et al., 2012).

Sea-level rise projections (5- and 95-percentile levels) were derived using the method described by Hunter et al. (2013) at 10-year intervals from 1990 to 2100 for the nine tide-gauge stations for the A1FI scenario (Neil White, CSIRO, pers. comm.), which is the IPCC SRES scenario providing the largest projected changes. In recent years, global climate trends have closely tracked the A1FI projections (Le Quéré et al., 2009). The scenario is now commonly used by decision-makers as the basis for responses to sea-level rise (Hunter, 2012). Here we use the regional A1FI projections as the basis for deriving sea-level rise allowances in Atlantic Canada. While the global-average sea-level rise has been reported for six emission scenarios (B1, B2, A1B, A1T, A2, A1FI; Meehl et al., 2007), results from AOGCMs are only available for scenarios B1, A1B and A2, of which scenario A2 is the closest to A1FI. Therefore, the spatially-varying A1FI projections were derived from spatially-varying A2 projections which were scaled using ratios of global-average projections for A1FI and A2.

The GIA model projections in Atlantic Canada (Table 2, column 6) vary strongly spatially. It includes the effects of the redistribution of ocean water in response to gravitational changes and vertical land motion of the ocean floor (Kendall et al., 2005). For the Maritimes, where there is small response of the Earth to changing water loads, the motion of the sea-surface due to GIA is only a few tenths of a millimeter per year. It should be pointed out that GIA model predictions incorporate relatively small adjustments to the surface of the ocean and so are not strictly vertical motion, and that the GPS observations incorporate a far-field elastic loading effect from mass changes in distant glaciers and ice sheets (which the GIA model does not incorporate), and so the comparison between GIA model predictions and GPS observations is not expected to be one to one. The difference between GIA and GPS is -0.6 ± 0.8 mm/yr. When comparing the points and the 1-to-1 line in Figure 3, it reveals that the GIA model predicts a larger rate of subsidence than observed with the GPS. The GIA model results (Table 2) show significant land subsidence in Nova Scotia and PEI, land uplift in the St Lawrence Estuary and Northern Gulf of St Lawrence in the twenty-first century. In this study, we use the GIA model predictions to generate allowances.

Table 4 summarizes the central value (the mean of the 5- and 95- percentile values) and 90% range of the projected regional sea-level change for 2050 relative to 1990 for the A1FI emission scenario for the nine tide-gauge stations. The projected central values suggest that sea level will rise between 26 to 35 cm in Scotian Shelf, Gulf of Maine and Newfoundland regions, and fall by 15 cm in Sept-Iles and remain approximately the same in St. Lawrence Estuary. Table 5 summarized the sea-level projections for the period 1990-2100, with the mean values spanning from -15 to 84 cm, and the 90% confidence intervals spanning about 80 cm.

6. Regional sea-level allowances

Following Hunter (2012), the results are presented in two different ways. Firstly, a rise of mean sea level Δz increases the expected number of exceedances *N*, or reduces the return period by a factor of $exp\frac{\Delta z}{\lambda}$, which is determined by combined effect of the Gumbel scale parameter and the mean sea-level rise. In other words, the fixed level is flooded $exp\frac{\Delta z}{\lambda}$ more times when the mean sea level is raised by Δz.

This factor (Table 4) shows significant spatial variation for Atlantic Canada with a range of 0.3 to 45 for the period 1990-2050. The largest values of this multiplying factor are in St John's Newfoundland, coinciding with the smallest value of the scale parameter. The factors are small in St. Lawrence Estuary and Northern Gulf of St. Lawrence, due to small amount of sea-level rise and sea level fall, respectively. While the mean sea-level rise is similar for Charlottetown and St. John's, the multiplying factor depends only on the spatially-varying scale parameter, and shows a large difference between the two stations, being 6 and 45 respectively.

In comparison with the period 1990-2100, the number of flooding events (Table 5) will increase by a factor of 104-12892 on Scotian Shelf, Gulf of Maine and Newfoundland, increase slightly by a factor of 4 in St Lawrence Estuary and decrease in northern Gulf of St. Lawrence. One way to interpret the factor of $exp\frac{\Delta z}{\lambda}$ is that a flooding event that occurred on average every R years in the past will occur every $R/exp\frac{\Delta z}{\lambda}$ years. For example, in St John's, a 50-year flooding event in the past will become an annual flooding event for period 1990-2050 (50/45 = 1 yr), and will occur every day for period 1990-2100 (50*365/12892=1.4 day).

The other way of presenting the results is in terms of the sea-level rise allowances for a normal uncertainty distribution. The allowance is composed of two parts: the mean sea-level rise (Δz) and the term $\frac{\sigma^2}{2\lambda}$ arising from the uncertainty in future sea-level rise. For the A1FI emission scenario and the period 1990-2050, the allowance (Table 4) ranges from -13 to 38 cm and is slightly greater than the mean projections of sea-level rise by 1-4 cm. For comparison, Table 5 shows that the allowance for the period 1990-2100 ranges from 7 to 108 cm and is much larger than the corresponding mean projection by 17-30 cm. This increase in the difference between the allowance and the mean projection (Appendix B) lies in the increasing uncertainty of sea-level projections with time. The allowances for different periods (Appendix B) are always within the 95-percentile upper limit of regional sea-level projections at all tide-gauge stations. The sea-level allowance also shows a significant spatial variation (Fig. 6), largely affected by spatially-varying projections of sea-level rise.

The vertical allowances generated by GIA model projections are larger (more pessimistic) than you would get using the GPS rates. This level of pessimism is about 3 cm for a period of 50 years (0.6 mm/y * 50 years = 3 cm). Incorporating GPS rates is beyond the scope of the report, but the direct comparison between GIA model projections and GPS observations suggests that future adjustments will only be at the level of a few centimeters at the nine tide gauge stations, compared to the many tens of centimeters of the A1FI projection.

7. Conclusions

This report provides a brief overview of the scientific basis and the methodology for deriving sea-level allowances for Atlantic Canada. The tide-gauge data has been analyzed to determine the present trend of relative sea-level rise and the statistics of storm tides. The GPS rates were introduced to (a) compare to the rate of relative sea-level rise at tide gauge stations and to determine an "absolute" 20th century sea-level rise to assess the dual consistency of tide gauge trends and GPS vertical land motion, and (b) to compare to the GIA model projections to show general agreement between the modeled rates and the observations.

The return levels have been derived from a Gumbel extreme values distribution fitted to the cumulative distribution function of ranked annual maxima of hourly water levels (with annual means removed) in Atlantic Canada. The 50-year return level is due to the combined effect of large tides and large surges, while the 1-year return level is primarily determined by tides. The number of exceedances and exceedance probability were estimated for any given period (asset life, Appendix A, Figs 7-14).

The regional projections of sea-level rise employed in this report (Appendix A, Tables 6-14, Columns 2-4) include the effect of thermal expansion, land ice melting, ocean dynamics, GIA and fingerprints, and are based on Church et al. (2011) and Hunter et al. (2013). For the A1FI emission scenario and for the period of 1990-2050, the sea-level is most likely to rise between 26 and 35 cm in Scotian Shelf, Gulf of Maine and Newfoundland regions, to rise between 0 and 6 cm in St. Lawrence Estuary, and to fall by 15 cm in the Northern Gulf of St. Lawrence. Sea-level rise will increase the frequency of flooding events by a factor of up to 45 for the period of 1990-2050, and by a factor of up to 12892 for the period of 1990-2100. It should be emphasized that these are only based on the results from the nine tide gauge sites considered here and so the range of factors for the region could be larger than stated here.

In most regions of Atlantic Canada, new infrastructure will need to be built higher to account for future sea-level rise. The vertical allowances for the 21st century at 10-year intervals (Appendix A, Tables 6-14, Column 5) have been derived at nine tide-gauge stations for the Atlantic Canada following the latest work of Hunter et al. (2013). This allowance depends only on the projected rise in mean sea level and its uncertainty, and on the scale parameter of a Gumbel distribution. An attractive feature of this allowance is that it does not require that the expected number of exceedances be prescribed. The range of future allowances for 1990-2050 is between -13 and 38 cm, while the range for 1990-2100 is between 7 and 108 cm (Tables 4 and 5, Column 5). In the Bay of Fundy and Gulf of Maine, the vertical allowances in this region should also take account of the change in tidal amplitude, as the predicted tidal amplitude will increase over the next century in this region (Greenberg et al., 2012).

8. Future steps

The allowances in this report are only provided up until 2100 relative to 1990 to align with projections provided by the IPCC fourth assessment report. It should be noted that sea level is expected to continue to rise beyond 2100 (Schaeffer et al., 2012). Both the 2050 and 2100 sea level allowances in Atlantic Canada should be reviewed following the release of the IPCC's Fifth Assessment Report (AR5). The Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) is developing AR5 versions of the regional sea-level projections, but they will not be available until the AR5 Working Group I report is released in September 2013.

Atlantic Canada is a region where the GIA varies strongly spatially, and there are some areas with substantial disagreement between GIA model and GPS vertical motion rates. Substituting the GPS rates as a component of regional sea-level rise will require a significant effort which could be carried out if a more comprehensive project is funded in future years.

Recent studies suggest that there is a strong regional component of sea-level rise associated with dynamic oceanographic effects (Yin et al., 2010; Sallenger et al., 2012; Yin, 2012). Future revisions could incorporate the latest modelling results and will probably lead to increases in projections of mean sea level and in sea-level allowances.

For future years, it would be possible to extend the tool to the Canadian Pacific and Arctic coasts. This would require collection of all tide-gauge and GPS data, as well as regional sea-level projections in those areas. The newly compiled and complete Canadian tide-gauge data set could potentially contribute to GESLA (Global Extreme Sea-Level Analysis) sea-level database (Menéndez and Woodworth, 2010). In the Arctic, we should be aware of the difficulty to implement the sea-level tool because of the lack of historical tide gauge records.

In future years, it would also be possible to include storm-surge model results to provide the scale parameters for areas where there are no tide-gauge data. This would require discussion with Dr. Jinyu Sheng (Dalhousie University) and Dr. David Greenberg (DFO) regarding the possibility of utilizing storm-surge model in the Northwest Atlantic based on existing models that they maintain. On the Canadian Pacific coast, it may be possible to get storm-surge model outputs from Dr. Richard Thomson (DFO), but the Arctic will remain a significant modeling challenge.

It would be useful to develop a web mapping service tool to provide information on sea level allowances to be used by SCH and RPSS. To simplify the online tool, a look-up-table of allowances at tide gauge stations can be provided and no on-line calculation is required. The service tool could be built on the IMF (Internet Mapping Framework) which uses ESRI's ArcIMS product. If needed, KML files could be generated for Google Earth application.

Acknowledgments

This work is funded by the DFO Aquatic Climate Change Adaptation Services Program (ACCASP). We would like to thank all those who participated in the October 18, 2012 workshop held at Bedford Institute of Oceanography. This is an output of the NRCan Climate Change Geoscience Program. Support from the NRCan Climate Change Impacts and Adaptation Division is gratefully acknowledged by Thomas S. James. We thank Yongsheng Wu and David A. Greenberg for their helpful reviews of the report.

Glossary of terms

ACCASP is the Aquatic Climate Change Adaptation Services Program of the federal Department of Fisheries and Oceans.

AOGCM is the atmosphere ocean general circulation model.

A1 emission scenario is an **IPCC** scenario that describes a future world of very rapid economic growth, a global population that peaks in the mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. See **SRES** below.

A1FI emission scenario is an **IPCC** scenario is a fossil intensive and high economic growth scenario, the highest SRES scenario, and belongs to the **A1** storyline and scenario family. See **SRES** below.

Cumulative distribution function (*F*) is the probability that there will be no exceedances during the prescribed period.

Exceedance events are events which occur when water levels exceed a given level.

Exceeding probability (*E*) is the probability of at least one exceedance event happening during a given period.

Glacial isostatic adjustment (GIA), also called postglacial rebound, is the delayed response of the Earth to surface unloading caused by deglaciation at the end of the last Ice Age.

IPCC is the Intergovernmental Panel on Climate Change.

Period *T* is associated with the life of a coastal asset, such as a building or other infrastructure.

RPSS stands for Real Property, Safety and Security, a sector of the federal Department of Fisheries and Oceans.

SCH stands for Small Craft Harbours, a sector of the federal Department of Fisheries and Oceans.

SRES is the Special Report on Emissions Scenarios, published by the IPCC in 2000 (Nakicenovic et al., 2000). It has provided the climate projections for the Fourth Assessment Report (**AR4**) of the IPCC. **SRES** scenarios do not include mitigation assumptions. Since then, a new set of four scenarios, known as the representative concentration pathways (**RCP**s, van Vuuren et al., 2011) has been designed, which includes mitigation pathways. The Fifth Assessment Report (**AR5**) will be based on these.

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TABLES

Table 1: Summary of tide-gauge data at stations located along the east coast of Canada. The data were from beginning year to 2011. The columns are defined as follows: (1) station name, (2) linear trend and standard error in the annual means, in mm/yr, calculated using all available years, (3) beginning year when tide-gauge stations were implemented, and (4) record length used for the extreme value analysis.

Sea-Level Station	Rate of Relative SLR (mm/yr)	Beginning Year	Record Length (> 6 months per year) (yr)
Charlottetown	3.2 ±0.1	1911	87
Halifax	3.2 ±0.1	1895	94
North Sydney	3.6 ±0.4	1970	42
Quebec	-0.6 ±0.6	1961	50
Rimouski	1.3 ±0.9	1984	27
Saint John	2.2 ±0.1	1896	96
Sept-Iles	1.7 ±0.5	1972	39
St. John’s	2.3 ±0.3	1935	58
Yarmouth	3.6 ±0.3	1956	46

Table 2: Summary of GPS measurements and GIA model results. The columns are defined as follows: (1) station names, (2) the length of GPS records, (3) vertical land motion rates, positive indicates land uplift, (4) linear regression error, (5) total uncertainty including reference frame error and linear regression error, and (6) GIA model predictions of vertical crustal motion and sea-level change (Kendall et al., 2005), positive indicates that ocean surface is falling relative to land.

Sea-Level Station	T (year)	Vup (mm/yr)	Regression Error (mm/yr)	Total Uncertainty (mm/yr)	GIA Model Prediction (mm/yr)
Charlottetown (SHE2)	4.4	-0.3	0.3	0.6	-1.4
Halifax	9.3	-1.1	0.1	0.6	-2.2
North Sydney	16.6	-1.8	0.3	0.6	-1.9
Quebec	9.9	3.5	0.2	0.6	2.1
Rimouski	6.5	3.1	0.2	0.6	2.9
Saint John	5.5	-0.6	0.2	0.6	-0.9
Sept-Iles	5.5	4.6	0.2	0.6	5.3
St. John’s	11.3	0.1	0.1	0.5	-1.7
Yarmouth	15.7	-1.4	0.3	0.6	-1.8

Table 3: Statistics of storm tides. The columns are defined as follows: (1) station names, (2) location parameter of Gumbel distribution, (3) scale parameter of Gumbel distribution, and (4) 50-year return levels.

Sea-Level Station	Location Parameter (cm)	Scale Parameter (cm)	50-year Return Level (cm)
Charlottetown	152	16	213
Halifax	134	10	172
North Sydney	101	12	148
Quebec	368	18	437
Rimouski	265	10	304
Saint John	428	11	470
Sept-Iles	205	14	258
St. John’s	109	8	141
Yarmouth	261	10	303

Table 4: Summary of projected sea-level change and future sea-level extremes for the period 1990-2050 at nine tide-gauge stations. The columns are defined as follows: 1) tide-gauge station, 2) 5-percentile level, 3) mean of the 5- and 95-percentile levels, 4) 95-percentile level of projections of sea-level rise, 5) sea-level rise allowance, and 6) factor by which frequency of flooding events will increase with a sea-level rise of Δz.

Sea level Station	Projection 5% (cm)	Projection Mean Δz (cm)	Projection 95% (cm)	Allowance (cm)	Factor
Charlottetown	16	29	42	31	6
Halifax	21	35	48	38	34
North Sydney	19	32	45	35	15
Quebec	-7	6	19	7	1
Rimouski	-13	0	13	3	1
Saint John	11	26	40	29	11
Sept-Iles	-28	-15	-2	-13	0.3
St. John’s	19	31	43	34	45
Yarmouth	18	32	46	36	22

Table 5: Summary of projected sea-level change and future sea-level extremes for the period 1990-2100 at nine tide-gauge stations. The columns are defined as follows: 1) tide-gauge station, 2) 5-percentile level, 3) mean of the 5- and 95-percentile levels, 4) 95-percentile level of projections of sea-level rise, 5) sea-level rise allowance, and 6) factor by which frequency of flooding events will increase with a sea-level rise of Δz.

Sea level Station	Projection 5% (cm)	Projection Mean Δz (cm)	Projection 95% (cm)	Allowance (cm)	Factor
Charlottetown	33	73	113	92	104
Halifax	49	84	119	108	5245
North Sydney	39	78	118	103	740
Quebec	-14	26	66	43	4
Rimouski	-25	15	56	45	4
Saint John	29	67	106	93	520
Sept-Iles	-56	-15	25	7	0.3
St. John’s	41	77	113	107	12892
Yarmouth	42	80	119	106	2152

Figures

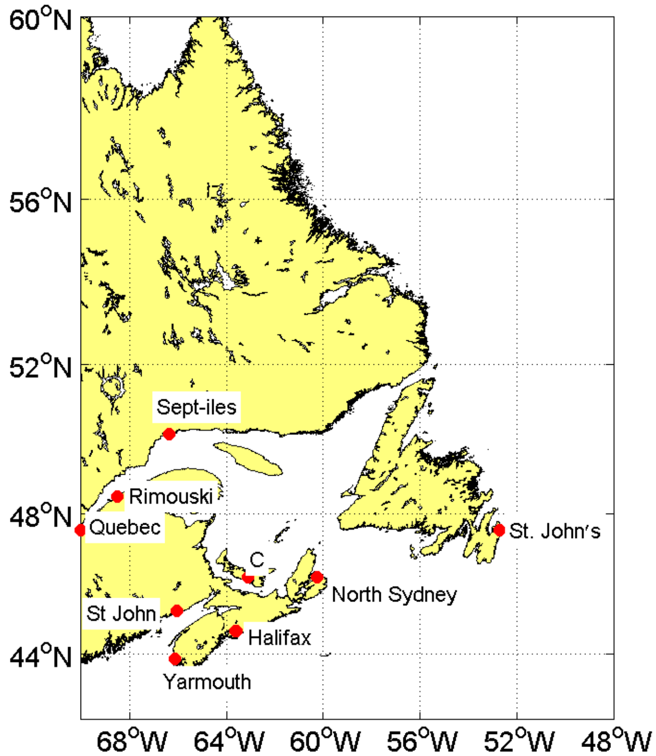

Figure 1: Map showing tide gauge stations which have records of water levels longer than 25 years. C is Charlottetown.

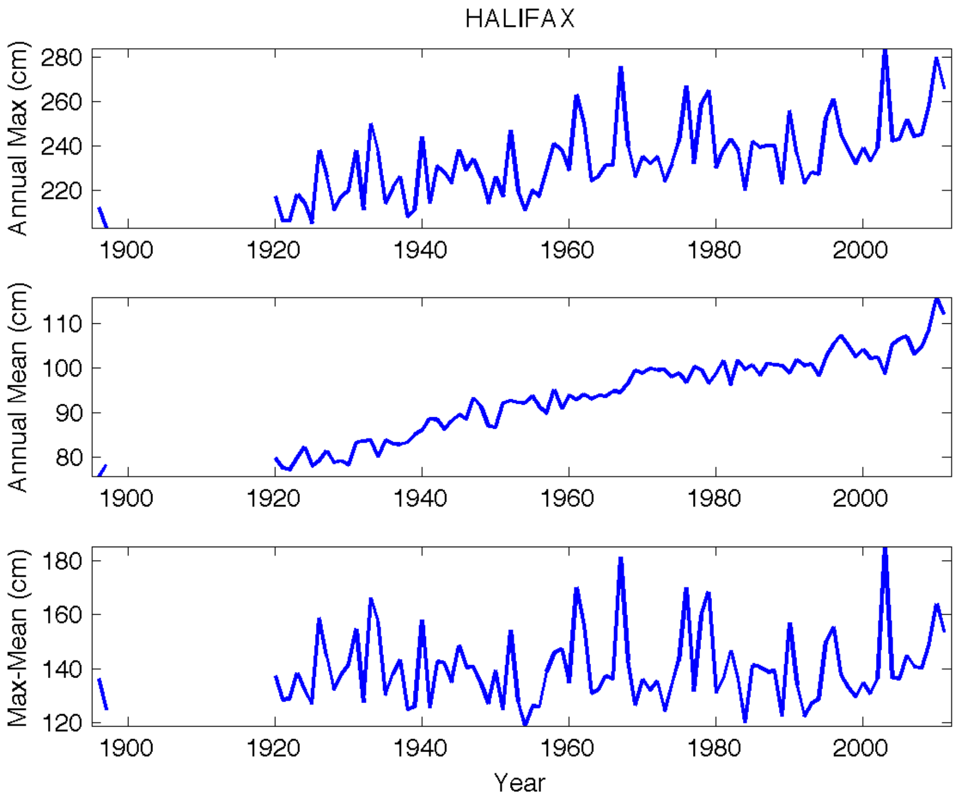

Figure 2: (top) Annual maxima of hourly water levels, (middle) annual means of hourly water levels, and (bottom) adjusted annual maxima with annual means removed in Halifax.

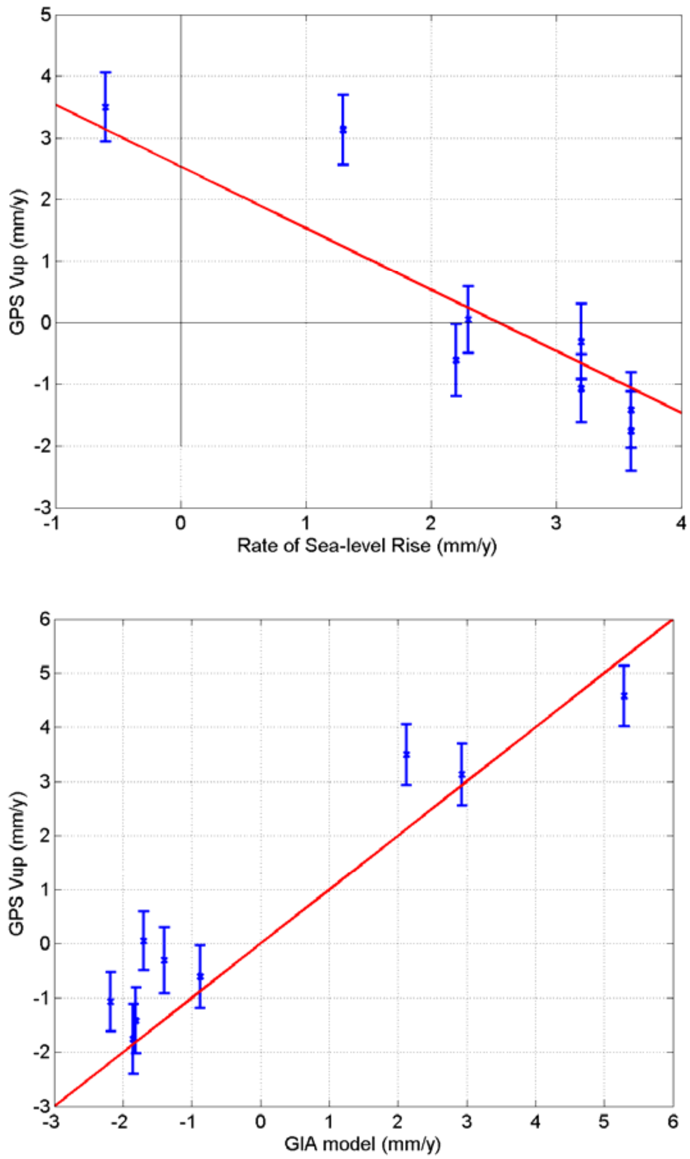

Figure 3: (top) Rate of relative sea-level rise (mm/yr) derived from tide-gauge data versus vertical velocity of land motion derived from GPS records. The linear curve has a slope of -1 and an intercept of 2.5 mm/yr equal to the rate of sea-level rise in a situation where the vertical land motion is zero. (bottom) vertical land motion computed by the GIA model (Kendall et al., 2005) versus the vertical land motion derived from GPS measurements.

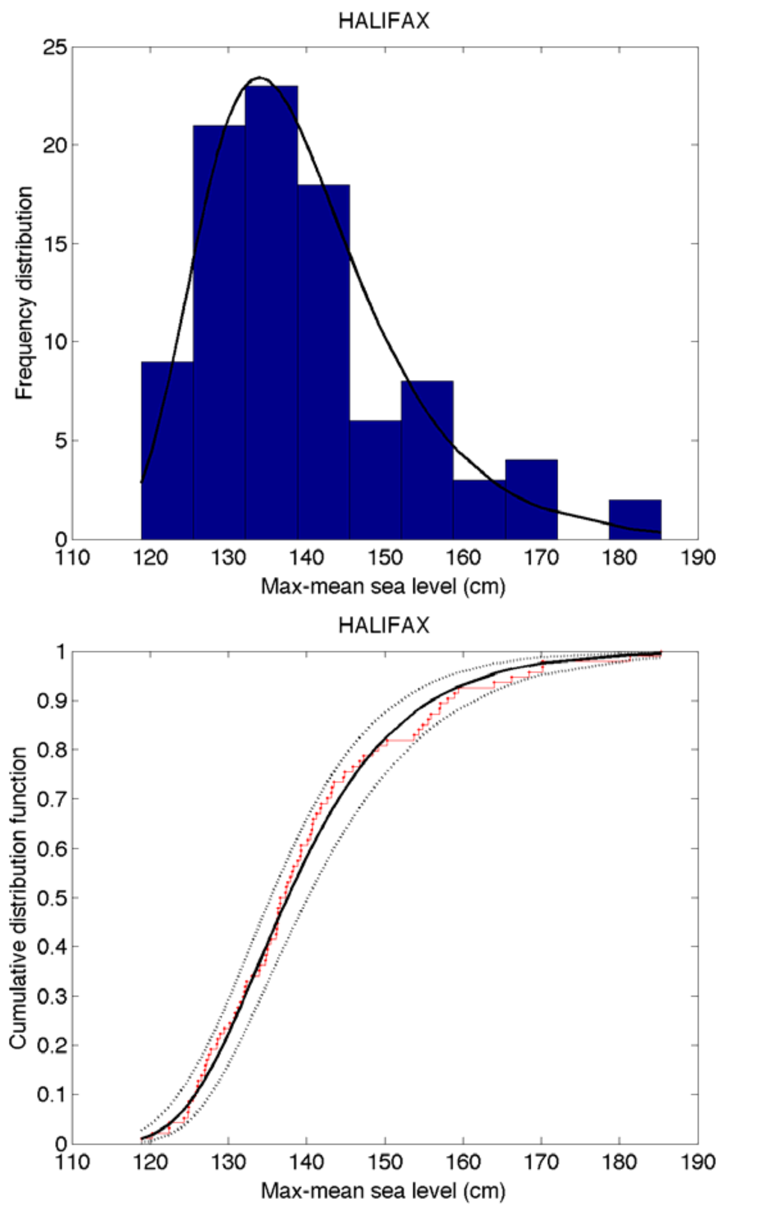

Figure 4: Diagnostic plots of Gumbel fit to the adjusted annual maxima of water levels in Halifax. (top) Histogram of the data and the corresponding Gumbel probability density function; (bottom) Cumulative distribution function (black line) and 5% to 95% percentile range (dashed lines) for adjusted annual maxima. Red dots are the ranking of adjusted annual maximum water levels.

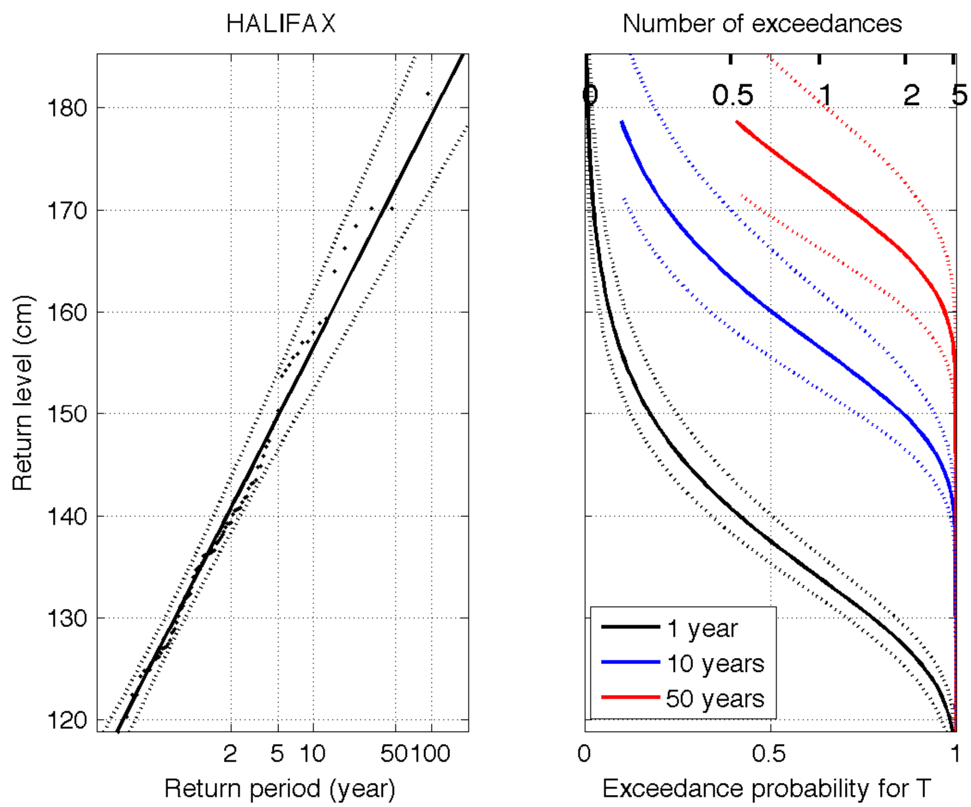

Figure 5: (left) the return level plot, (right) exceedance probabilities and number of exceedances for Halifax, for a given period of 1, 10 and 50 years. Solid lines are maximum likelihood curves and dashed lines show 5% to 95% percentile range. The blue and red curves are terminated at the low-probability end of the plot when the return level exceeds 100 years.

APPENDIX A: Statistics of tides and storm surges

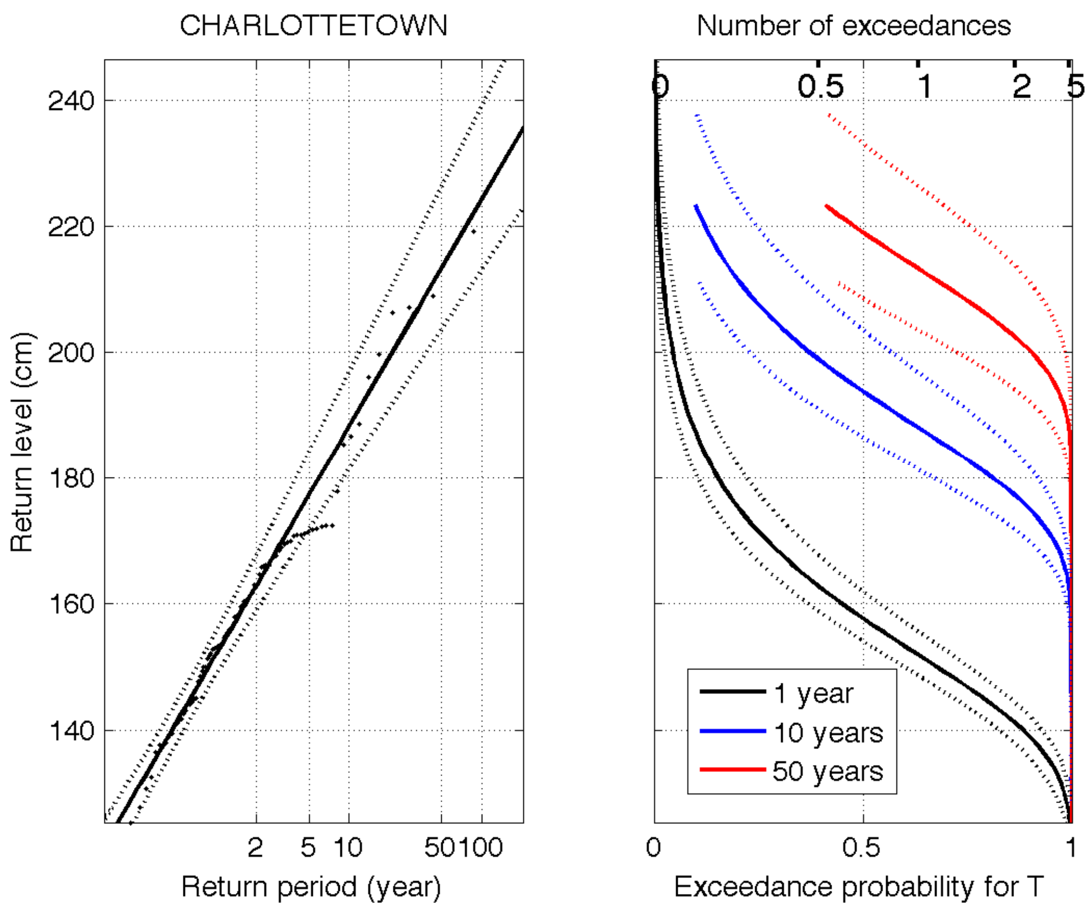

Figure 6: (left) the return level plot, (right) exceedance probabilities and number of exceedances for Charlottetown, for a given period of 1, 10 and 50 years. Solid lines are maximum likelihood curves and dashed lines show 5% to 95% percentile range.

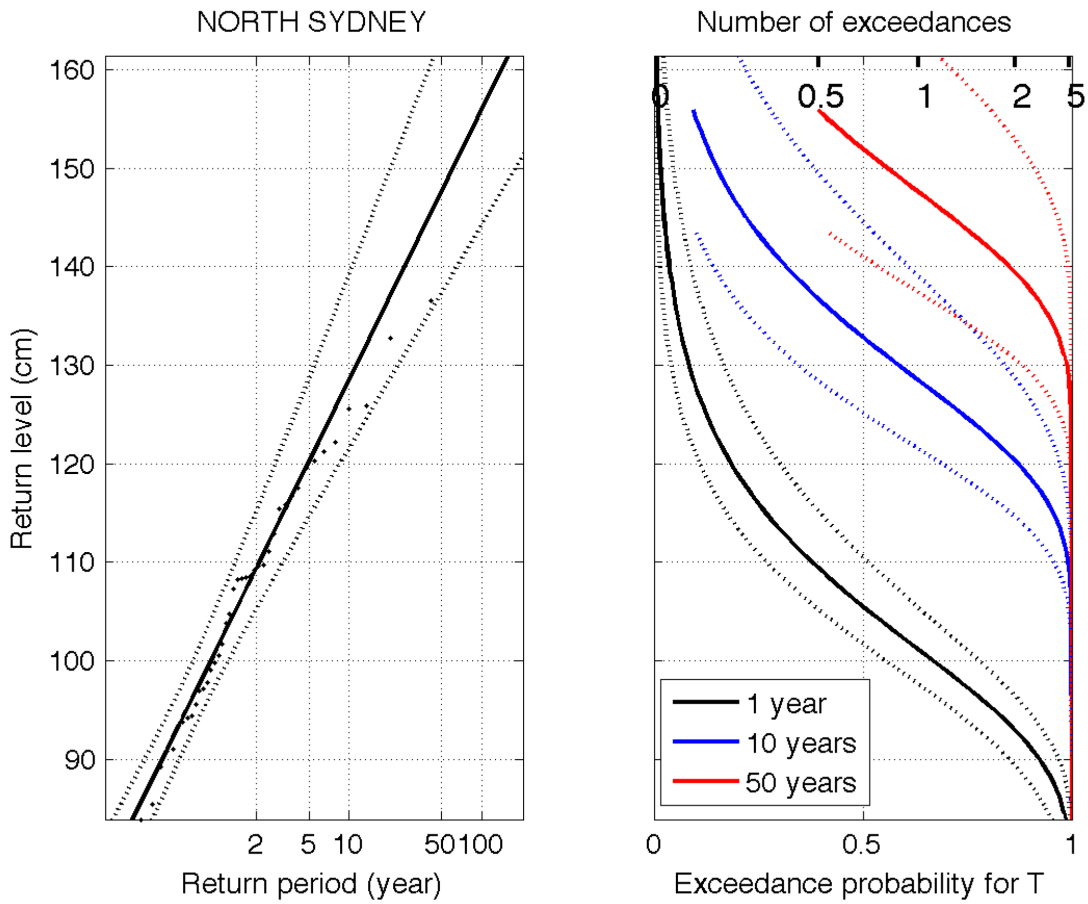

Figure 7: (left) the return level plot, (right) exceedance probabilities and number of exceedances for North Sydney, for a given period of 1, 10 and 50 years. Solid lines are maximum likelihood curves and dashed lines show 5% to 95% percentile range.

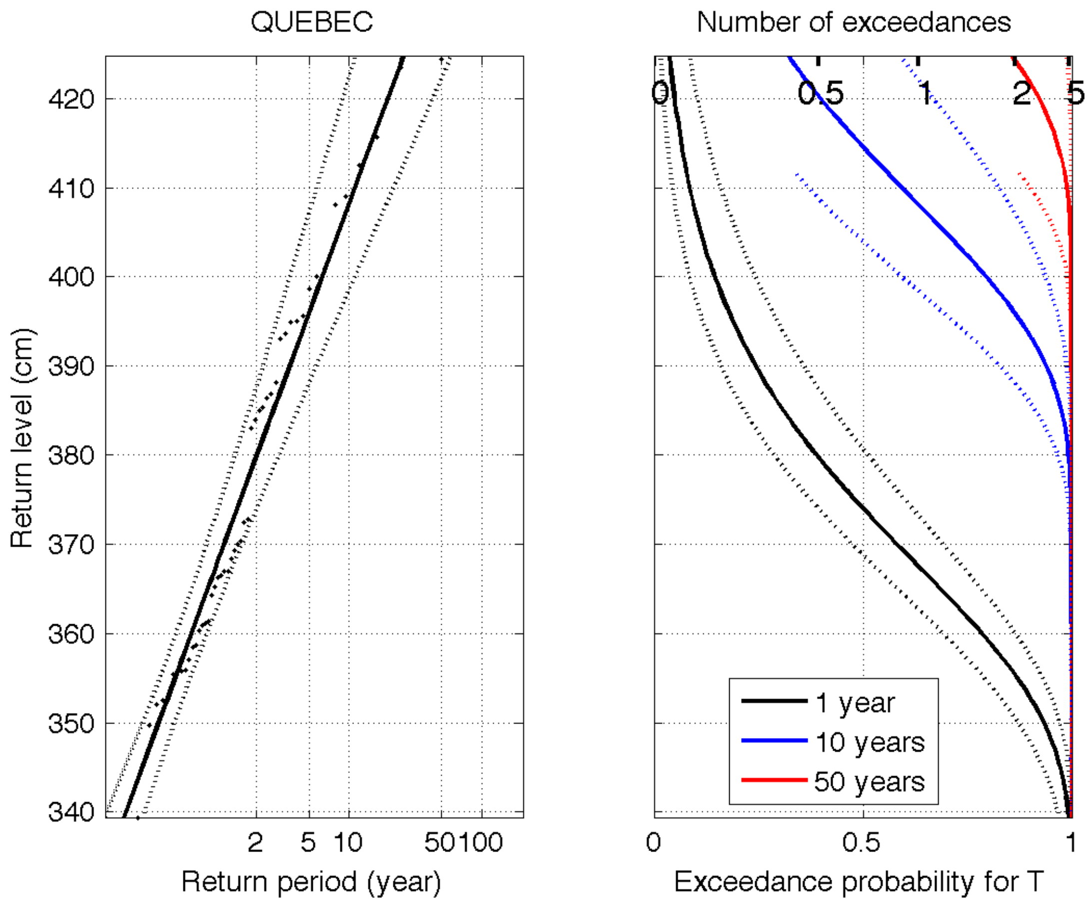

Figure 8: (left) the return level plot, (right) exceedance probabilities and number of exceedances for Quebec City, for a given period of 1, 10 and 50 years. Solid lines are maximum likelihood curves and dashed lines show 5% to 95% percentile range.

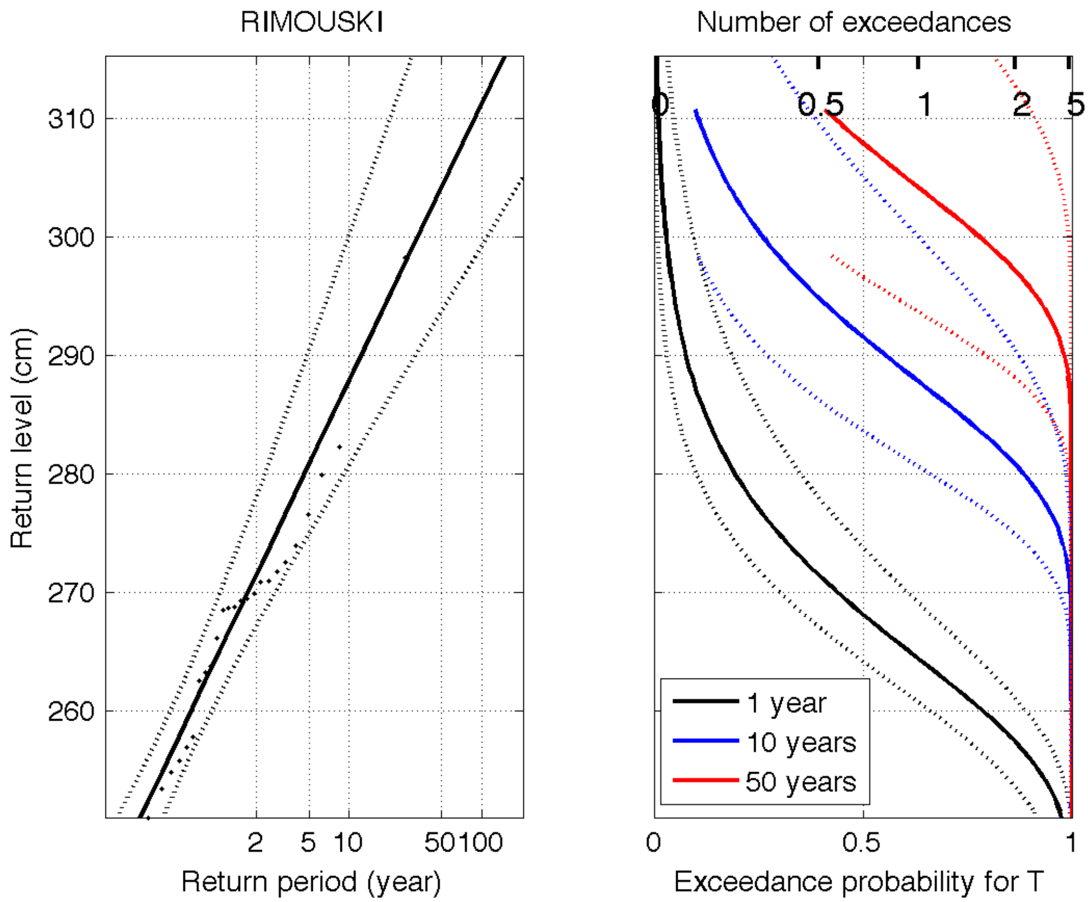

Figure 9: (left) the return level plot, (right) exceedance probabilities and number of exceedances for Rimouski, for a given period of 1, 10 and 50 years. Solid lines are maximum likelihood curves and dashed lines show 5% to 95% percentile range.

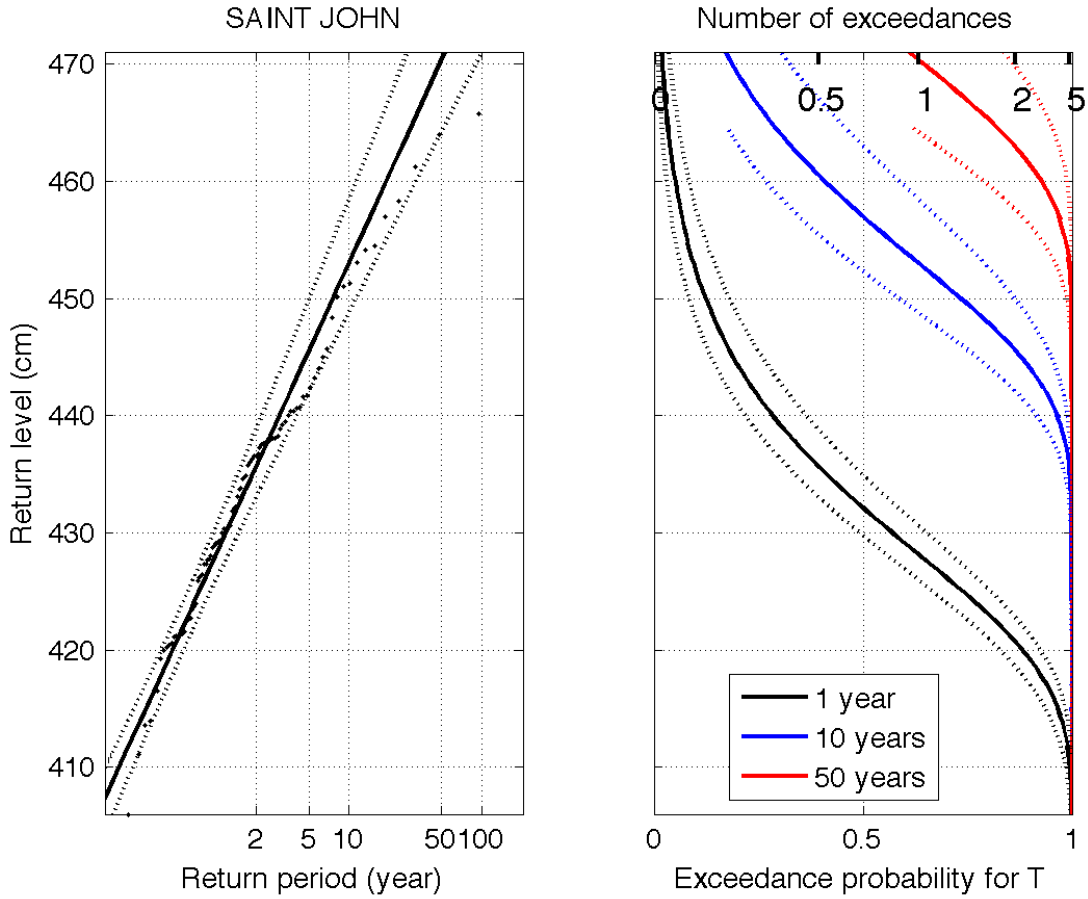

Figure 10: (left) the return level plot, (right) exceedance probabilities and number of exceedances for Saint John, New Brunswick, in the Bay of Fundy, for a given period of 1, 10 and 50 years. Solid lines are maximum likelihood curves and dashed lines show 5% to 95% percentile range.

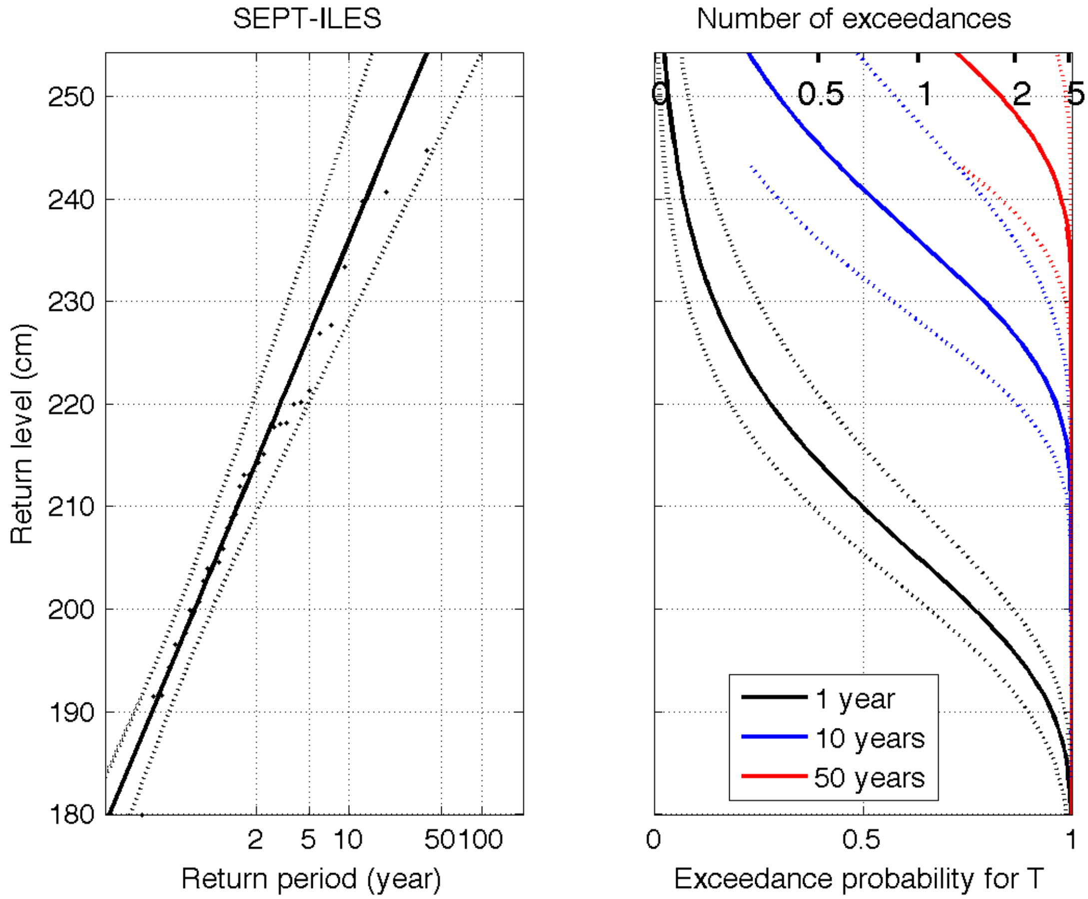

Figure 11: (left) the return level plot, (right) exceedance probabilities and number of exceedances for Sept-Iles, for a given period of 1, 10 and 50 years. Solid lines are maximum likelihood curves and dashed lines show 5% to 95% percentile range.

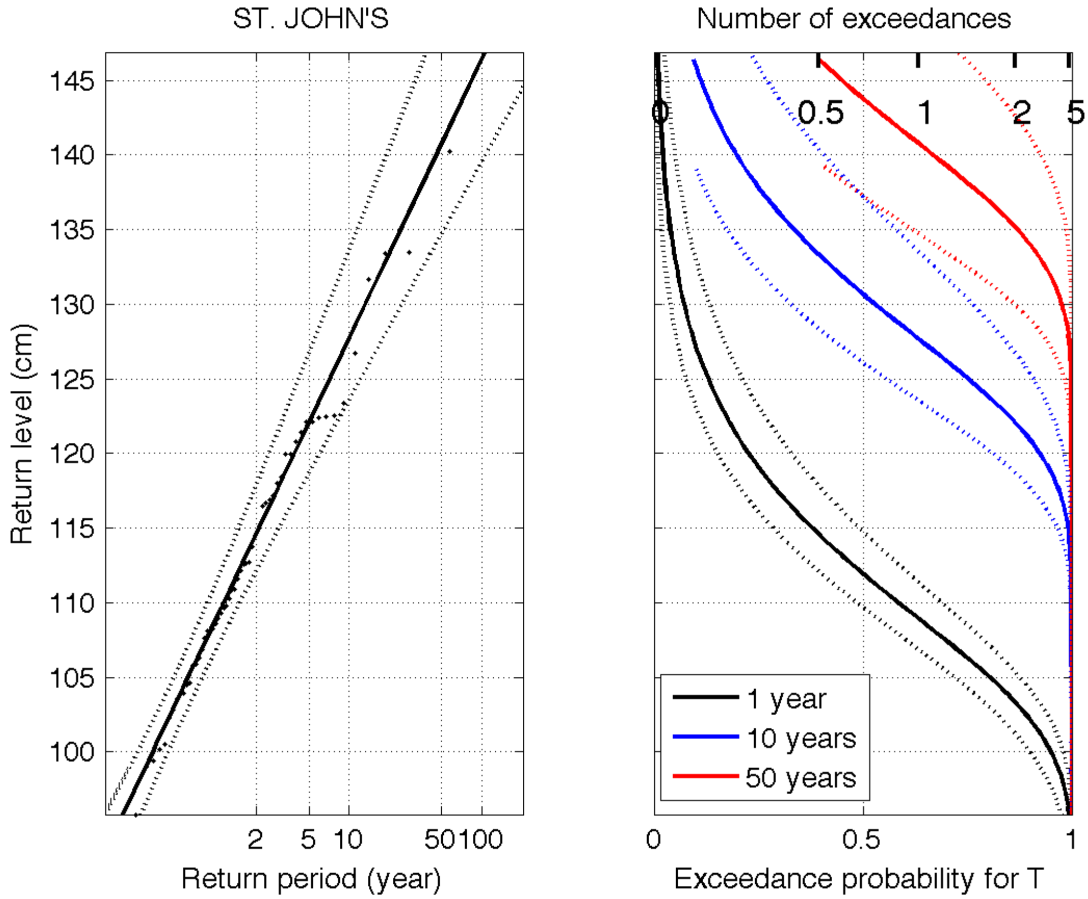

Figure 12: (left) the return level plot, (right) exceedance probabilities and number of exceedances for St. John's, Newfoundland, for a given period of 1, 10 and 50 years. Solid lines are maximum likelihood curves and dashed lines show 5% to 95% percentile range.

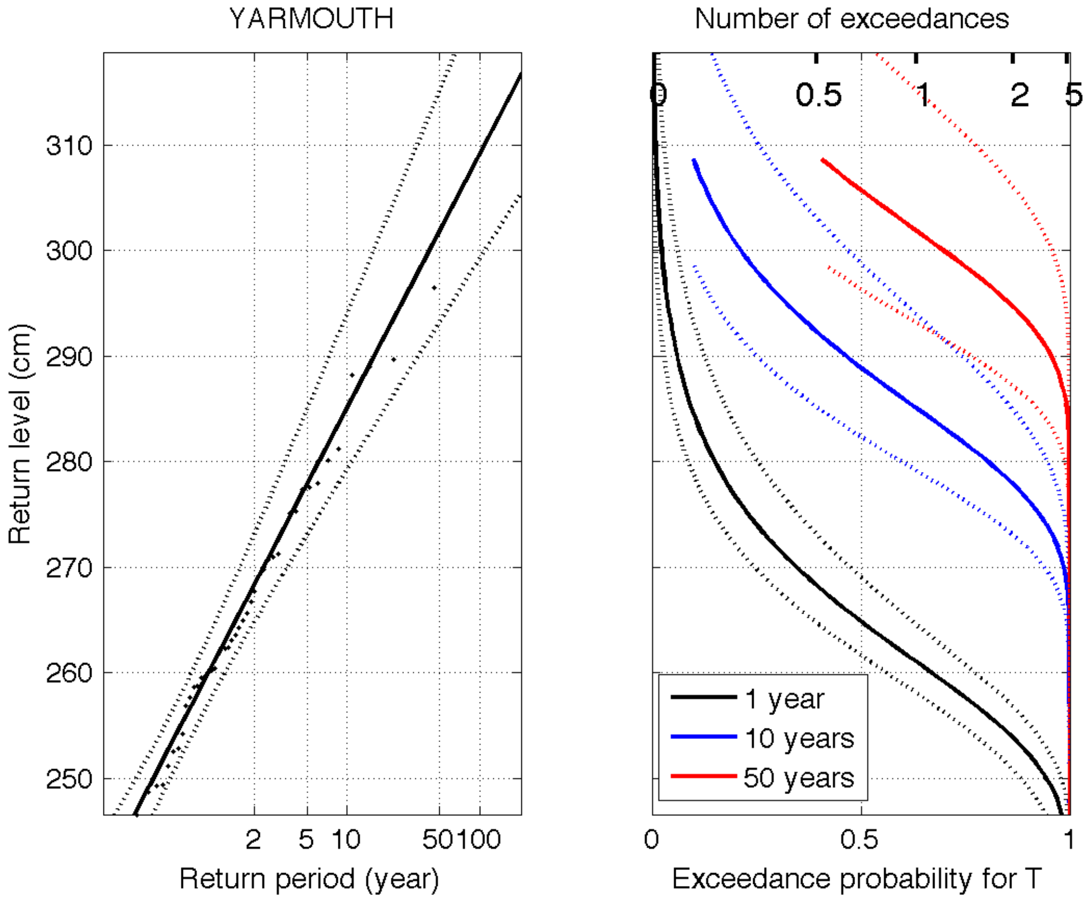

Figure 13: (Left) the return level plot, (right) exceedance probabilities and number of exceedances for Yarmouth, for a given period of 1, 10 and 50 years. Solid lines are maximum likelihood curves and dashed lines show 5% to 95% percentile range.

APPENDIX B: Summary of values for each tide-gauge location and for a spatially-varying sea-level rise

Table 6: Summary of projected sea-level change and future sea-level extremes for future periods with respect to year 1990 at 10-year intervals in Charlottetown. The columns are defined as follows: 1) year (calendar year average), 2) 5-percentile level, 3) mean of the 5- and 95-percentile levels, 4) 95-percentile level of projections of sea-level rise, 5) sea-level rise allowance, and 6) factor by which frequency of flooding events will increase with a sea-level rise of Δz.

Year	Projection 5% (cm)	Projection Mean (cm)	Projection 95% (cm)	Allowance (cm)	Factor
2000	2	4	5	4	1
2010	4	8	13	9	2
2020	5	13	21	14	2
2030	9	18	27	19	3
2040	13	23	33	24	4
2050	16	29	42	31	6
2060	21	37	53	40	11
2070	26	46	65	50	18
2080	28	54	80	62	32
2090	31	64	96	76	58
2100	33	73	113	92	104

Table 7: Summary of projected sea-level change and future sea-level extremes for future periods with respect to year 1990 at 10-year intervals in Halifax. The columns are defined as follows: 1) year (calendar year average), 2) 5-percentile level, 3) mean of the 5- and 95-percentile levels, 4) 95-percentile level of projections of sea-level rise, 5) sea-level rise allowance, and 6) factor by which frequency of flooding events will increase with a sea-level rise of Δz.

Year	Projection 5% (cm)	Projection Mean (cm)	Projection 95% (cm)	Allowance (cm)	Factor
2000	3	5	7	5	2
2010	6	10	14	10	3
2020	10	16	22	16	5
2030	14	21	28	22	9
2040	18	28	37	29	16
2050	21	35	48	38	34
2060	28	43	59	48	83
2070	35	53	72	60	227
2080	40	63	87	74	618
2090	44	73	103	89	1771
2100	49	84	119	108	5245

Table 8: Summary of projected sea-level change and future sea-level extremes for future periods with respect to year 1990 at 10-year intervals in North Sydney. The columns are defined as follows: 1) year (calendar year average), 2) 5-percentile level, 3) mean of the 5- and 95-percentile levels, 4) 95-percentile level of projections of sea-level rise, 5) sea-level rise allowance, and 6) factor by which frequency of flooding events will increase with a sea-level rise of Δz.

Year	Projection 5% (cm)	Projection Mean (cm)	Projection 95% (cm)	Allowance (cm)	Factor
2000	3	4	5	4	1
2010	5	9	14	9	2
2020	7	15	23	16	3
2030	11	20	29	21	5
2040	15	26	36	27	9
2050	19	32	45	35	15
2060	24	40	57	45	30
2070	30	50	70	56	66
2080	33	59	85	70	144
2090	36	68	101	85	320
2100	39	78	118	103	740

Table 9: Summary of projected sea-level change and future sea-level extremes for future periods with respect to year 1990 at 10-year intervals in Quebec City. The columns are defined as follows: 1) year (calendar year average), 2) 5-percentile level, 3) mean of the 5- and 95-percentile levels, 4) 95-percentile level of projections of sea-level rise, 5) sea-level rise allowance, and 6) factor by which frequency of flooding events will increase with a sea-level rise of Δz.

Year	Projection 5% (cm)	Projection Mean (cm)	Projection 95% (cm)	Allowance (cm)	Factor
2000	-1	0	2	0	1
2010	-3	1	6	1	1
2020	-6	2	11	3	1
2030	-6	3	12	4	1
2040	-6	4	15	5	1
2050	-7	6	19	7	1
2060	-8	8	25	11	2
2070	-8	12	32	16	2
2080	-10	16	42	23	2
2090	-12	21	54	32	3
2100	-14	26	66	43	4

Table 10: Summary of projected sea-level change and future sea-level extremes for future periods with respect to year 1990 at 10-year intervals in Rimouski. The columns are defined as follows: 1) year (calendar year average), 2) 5-percentile level, 3) mean of the 5- and 95-percentile levels, 4) 95-percentile level of projections of sea-level rise, 5) sea-level rise allowance, and 6) factor by which frequency of flooding events will increase with a sea-level rise of Δz.

Year	Projection 5% (cm)	Projection Mean (cm)	Projection 95% (cm)	Allowance (cm)	Factor
2000	-2	-1	1	-1	1
2010	-5	0	4	0	1
2020	-8	0	8	1	1
2030	-9	0	8	1	1
2040	-10	0	10	2	1
2050	-13	0	13	3	1
2060	-15	2	18	7	1
2070	-15	4	24	12	2
2080	-19	7	34	20	2
2090	-22	11	44	31	3
2100	-25	15	56	45	4

Table 11: Summary of projected sea-level change and future sea-level extremes for future periods with respect to year 1990 at 10-year intervals in Saint John, New Brunswick, in the Bay of Fundy. The columns are defined as follows: 1) year (calendar year average), 2) 5-percentile level, 3) mean of the 5- and 95-percentile levels, 4) 95-percentile level of projections of sea-level rise, 5) sea-level rise allowance, and 6) factor by which frequency of flooding events will increase with a sea-level rise of Δz.

Year	Projection 5% (cm)	Projection Mean (cm)	Projection 95% (cm)	Allowance (cm)	Factor
2000	1	3	5	3	1
2010	3	7	12	8	2
2020	5	12	18	12	3
2030	9	16	24	17	4
2040	10	21	31	23	7
2050	11	26	40	29	11
2060	15	33	51	38	21
2070	20	41	62	49	46
2080	23	49	75	61	98
2090	26	58	90	76	222
2100	29	67	106	93	520

Table 12: Summary of projected sea-level change and future sea-level extremes for future periods with respect to year 1990 at 10-year intervals in Sept-Iles. The columns are defined as follows: 1) year (calendar year average), 2) 5-percentile level, 3) mean of the 5- and 95-percentile levels, 4) 95-percentile level of projections of sea-level rise, 5) sea-level rise allowance, and 6) factor by which frequency of flooding events will increase with a sea-level rise of Δz.

Year	Projection 5% (cm)	Projection Mean (cm)	Projection 95% (cm)	Allowance (cm)	Factor
2000	-4	-3	-2	-3	0.8
2010	-10	-5	0	-5	0.7
2020	-15	-7	1	-6	0.6
2030	-19	-10	-1	-9	0.5
2040	-23	-13	-2	-11	0.4
2050	-28	-15	-2	-13	0.3
2060	-33	-17	0	-13	0.3
2070	-37	-17	3	-12	0.3
2080	-44	-18	9	-8	0.3
2090	-50	-17	16	-2	0.3
2100	-56	-15	25	7	0.3

Table 13: Summary of projected sea-level change and future sea-level extremes for future periods with respect to year 1990 at 10-year intervals in St John's. The columns are defined as follows: 1) year (calendar year average), 2) 5-percentile level, 3) mean of the 5- and 95-percentile levels, 4) 95-percentile level of projections of sea-level rise, 5) sea-level rise allowance, and 6) factor by which frequency of flooding events will increase with a sea-level rise of Δz.

Year	Projection 5% (cm)	Projection Mean (cm)	Projection 95% (cm)	Allowance (cm)	Factor
2000	2	4	6	4	2
2010	6	9	13	10	3
2020	7	14	21	15	6
2030	12	20	27	21	11
2040	16	25	34	26	21
2050	19	31	43	34	45
2060	24	39	54	45	127
2070	29	49	68	57	392
2080	33	58	83	72	1261
2090	38	68	98	89	4126
2100	41	77	113	107	12892

Table 14: Summary of projected sea-level change and future sea-level extremes for future periods with respect to year 1990 at 10-year intervals in Yarmouth. The columns are defined as follows: 1) year (calendar year average), 2) 5-percentile level, 3) mean of the 5- and 95-percentile levels, 4) 95-percentile level of projections of sea-level rise, 5) sea-level rise allowance, and 6) factor by which frequency of flooding events will increase with a sea-level rise of Δz.

Year	Projection 5% (cm)	Projection Mean (cm)	Projection 95% (cm)	Allowance (cm)	Factor
2000	2	4	6	4	2
2010	5	9	14	10	2
2020	8	15	21	15	4
2030	13	20	28	21	7
2040	15	26	37	28	12
2050	18	32	46	36	22
2060	23	41	58	46	49
2070	29	50	71	58	123
2080	34	60	86	72	305
2090	38	70	102	88	801
2100	42	80	119	106	2152