CLIMATE-CHANGE IMPACTS IN THE COASTAL ZONE: IMPLICATIONS FOR ENGINEERING PRACTICE

Donald L. Forbes, Geological Survey of Canada, Bedford Institute of Oceanography, Dartmouth NS

ABSTRACT

Coastal impacts of anticipated climate change in Canada will result from rising sea level, changes in sea ice and open-water fetch (leading to increased storm wave energy), possible changes in storm tracks and intensity, and effects of warmer temperatures on coastal cliff and slope failure in northern regions with permafrost and massive ground ice. These changes will increase coastal hazards of engineering concern, including the frequency and magnitude of storm-surge flooding, storm-wave run-up, ice ride-up or pile-up, coastal slope failure, shoreline erosion and impacts on coastal infrastructure, among others. New technology provides opportunities for improved monitoring and hazard mapping, which are important requirements for planning and adaptation. Adaptation strategies may include a variety of hard and soft coastal protection, zoning and regulatory changes to encourage avoidance or retreat from the coast, planning, education, and other components.

RÉSUMÉ

L'impact sur les régions côtières du changement climatique anticipé au Canada sera lié à la hausse du niveau de la mer, aux transformations de la glace de mer et de l'étendue de mer sans glace (menant à une hausse de l'énergie des vagues), à des changements possibles du parcours et de l'intensité des tempêtes, et aux effets des températures plus élevées sur la stabilité des falaises côtières dans les régions du Nord affectées par la présence de pergélisol et de glace massive dans le sol. Suite à ces changements, on prévoit une augmentation des risques d'intérêt à l'ingénierie dans les zones côtières, qui incluent l'augmentation de la fréquence et de la magnitude des inondations causées par les ondes de tempête, du niveau de la limite d'action des vagues et de la pression des glaces, de l'instabilité des versants côtiers, de l'érosion littorale, et des impacts sur l'infrastructure, pour en nommer quelques-uns. Une technologie de pointe peut contribuer à la surveillance et à la cartographie des zones à risque, ces activités étant importantes dans un contexte d'aménagement et d'adaptation au changement climatique. Les stratégies d'adaptation pourront inclure une gamme de techniques plus ou moins sévères visant la protection des côtes, des changements aux règles affectant le zonage et l'aménagement pour encourager les utilisateurs à éviter les zones à risque ou à fonctionner en retrait de la côte, la planification, l'éducation du public, et autres mesures de ce genre.

1. INTRODUCTION

Climate change can include warming or cooling trends and changes in climate variability, including extreme events. In the coastal zone, it is important to determine flood probabilities, wave climate, and erosion rates under present rates of sea-level rise as a baseline for current adaptation requirements. Looking into the future, we then need to assess projected changes in coastal hazards under scenarios of climate warming, including accelerated rise in relative sea-level (RSL), increased storminess, reduced sea ice, accelerated thaw subsidence, and other factors. Appropriate planning, site selection, design, infrastructure and resource management, hazard mitigation and risk reduction depend on adequate understanding of RSL trends, changes in environmental forcing, long-term shoreline evolution and sediment budget issues, potential thresholds for rapid change, and the moving limits of hazard zones. New technology provides opportunities for improved monitoring and hazard mapping, which are important requirements for planning and adaptation. Adaptation strategies may include a variety of hard and soft engineering techniques, policy and regulatory changes, planning options, public education, and other components.

2. CLIMATE CHANGE IMPACTS AT THE COAST

Coastal impacts of anticipated climate warming in Canada will result from rising sea levels, changes in sea-ice conditions and open-water fetch (leading to increased storm-wave energy), possible changes in storm tracks and intensity, and effects of warmer temperatures on coastal cliff and slope failure, particularly in northern regions with permafrost and massive ground ice. These changes will increase coastal hazards of engineering concern, including the frequency and magnitude of storm-surge flooding, storm-wave run-up, ice ride-up or pile-up, coastal slope failure, shoreline erosion and impacts on coastal infrastructure, among others.

2.1 Relative sea-level rise

In many parts of Canada, changes are already underway, both in response to recent warming trends and resulting from additional non-climate processes (Figure 1). Relative sea level, the mean water level observed at a tide gauge, is rising along much of our coast, due in large part to regional crustal subsidence. In other areas, RSL is falling due to crustal uplift at a rate exceeding the regional sea-level rise. Subsidence and uplift arise primarily from the long-term isostatic response to changes in loading at the end of the last glaciation. Thus RSL in much of the Maritime Provinces has been rising over the past century at a mean rate of approximately 3 mm/year (equivalent to 0.3 m over 100 years), while RSL is falling along the Hudson Bay coast at rates of the order of 10 mm/a (>1 m per century) in some places. RSL changes on parts of the coast in southern Québec fall within a much smaller range plus or minus zero. Falling RSL creates engineering issues including harbour shoaling and permafrost development in emergent marine sediments. Rising RSL leads to increased flooding hazards and enhanced shoreline erosion. It can also induce saline intrusion into groundwater in susceptible settings, particularly if the groundwater table has been lowered by excessive withdrawal.

Prediction of future rates of RSL rise requires reliable estimates of global and regional mean sea-level rise as well as good knowledge of vertical crustal motion at any given location. The latest results from the Inter-governmental Panel on Climate Change in its Third Assessment Report (Church et al., 2001) project global mean sea-level rise between 0.09 m and 0.88 m over 110 years from 1990 to 2100, with most model outputs falling within a smaller range about a central value of 0.48 m. Because the rate of sea-level rise is expected to accelerate decade by decade, we can reasonably adopt an estimate of 0.5±0.3 m for the expected rise in global mean sea level over the coming century. Unfortunately, because various models produce very different output for the regional distribution of sea-level rise around the world (Church et al., 2001) and the response of sea-level to reduction of glacier and ice-sheet mass is geographically variable (Mitrovica et al., 2001), our ability to predict the sea-level rise on any given coast is limited.

Our understanding of vertical crustal motion is somewhat more advanced, with mature geophysical models providing good estimates of postglacial isostatic response and present rates of vertical motion (e.g. Dyke and Peltier, 2000; Douglas and Peltier, 2002; Peltier, 2004). At the same time, these models require validation on the ground. Estimates of the present rate of vertical motion at sites across Canada are slowly emerging from a network of GPS monitoring stations established by the Geodetic Survey Division and partners (Forbes et al., 2004a).

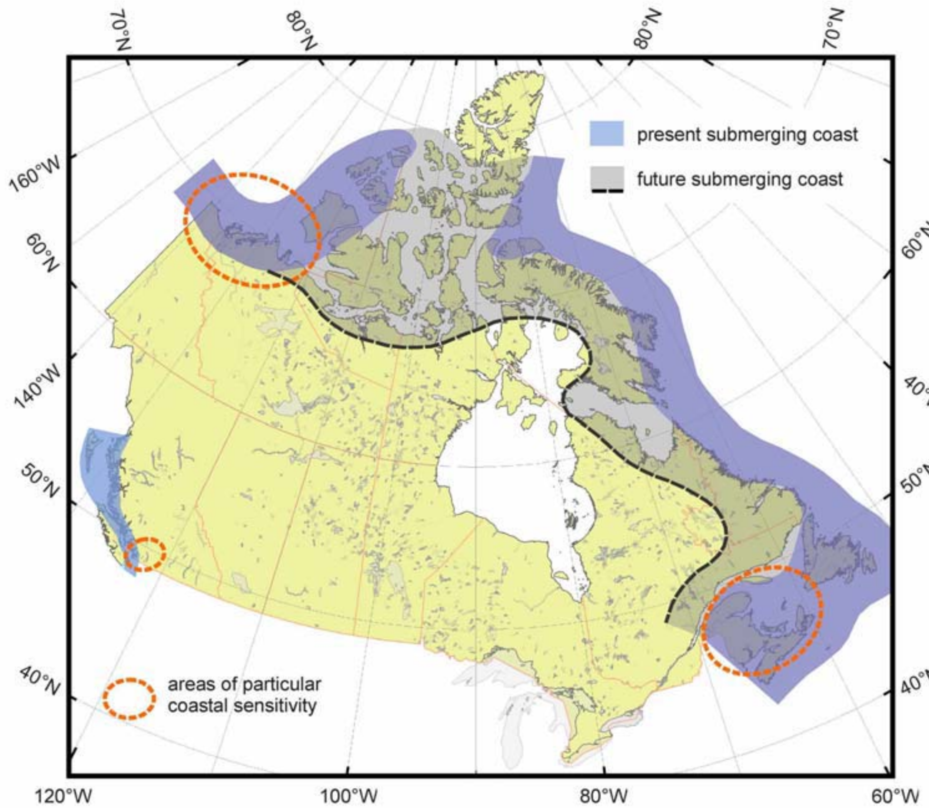

Figure 1. Parts of the coast of Canada presently undergoing submergence (darker shading), based on tide-gauge data and geological evidence of relative sea-level trends over the past 1000 years (Andrews, 1989). Lighter shading delimited by black broken line shows possible expanded zone of submergence with accelerated sea-level rise in the future (modified after Shaw et al., 1998). Ovals mark regions of exceptional coastal sensitivity to sea-level rise and climate warming.

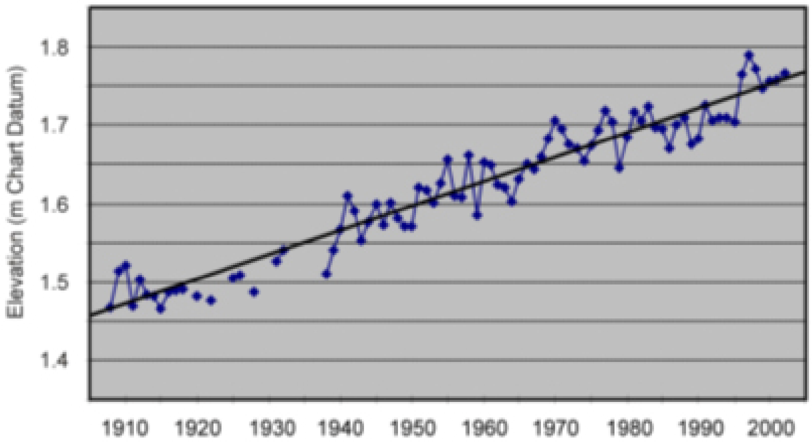

Figure 2. Time series of annual mean water level at Charlottetown (PEI) tide gauge, 1908-2002, showing a linear trend of relative sea level rising at 3.2 mm/year (r^2=0.93), after Parkes et al. (2002).

Fixed monuments of the Canadian Base Network (CBN) are used for repeat epoch GPS measurements at intervals of months to years, from which trends in the vertical elevation can be computed in relation to other stations in the network. Other stations, many of which are now co-located with tide gauges, have permanent GPS installations operating on a continuous basis (Forbes et al., 2004a).

Figure 1 shows the approximate extent of submerging coastline in Canada at the present time (after Shaw et al., 1998). This includes parts of the Pacific coast in British Columbia, most of the western Arctic coast, much of the east coast of Baffin Island, the island of Newfoundland, the Maritime Provinces, and parts of southern Québec. This reflects the present balance between global and regional sea-level rise and regional subsidence. It demonstrates that, regardless of any future impacts of climate change, sea-level rise is a factor in most parts of the country today and appropriate adaptation measures are required to reduce associated hazards.

As the rate of regional sea-level rise accelerates in future, assuming little change in the vertical motion, the rate of relative sea-level rise (the value observed by tide gauges) will accelerate at a comparable rate in areas presently undergoing submergence. A recent detailed analysis of tide-gauge data over almost 100 years (1908-2002) at Charlottetown, Prince Edward Island, revealed a long-term trend of rising relative sea level at a rate of 3.2 mm/year, equivalent to 0.32 m over the century (Figure 2; Parkes et al., 2002). That study concluded that vertical motion could account for as much as 0.2±0.1 m/century, from which the projected relative sea-level rise to 2100 was estimated at 0.7±0.4 m. At the low end, this indicates a continuation of the historical rate over the past 100 years (a rate to which the community is not adapted, as demonstrated by recent flooding events); at the high end, it suggests the possibility that relative sea-level rise may more than double, increasing by more than 1 m.

Other areas outside the region of present submergence will see a change in the balance between sea-level rise and vertical motion, leading to potentially large expansion in the extent of submerging coasts (Figure 1; Shaw et al., 1998). Defining the limits of present submergence and the possible extent of this expansion remains a primary research challenge for studies of coastal climate impacts in Canada (Forbes et al., 2004a).

2.2 Changes in sea ice

The effects of sea ice along the coast may be either protective or destructive, or a combination of the two (Forbes and Taylor, 1994). Sea ice is present in the St. Lawrence Estuary, the Gulf of St. Lawrence, the Bay of Fundy, and along parts of the Newfoundland coast for 3 to 4 months each winter. The length of the ice season increases northward from Labrador and from Hudson Bay into the Arctic Islands. In the Beaufort Sea region of the western Canadian Arctic, the ice season lasts for about 9 months and extensive areas of shallow water have bottomfast ice (Solomon et al., 2004). Where ice is present, it hinders the generation of surface gravity waves under wind stress, but may cause damage when driven ashore in ride-up or pile-up events (Figure 3).

Figure 3. Small ice pile-up at Maximeville, PEI,17January2004,impactedand severely damaged several houses alongthe shore.

Note sediment in ice in foreground. (DLF, Geological Survey of Canada, 2004-01-23).

The development of an icefoot on the beach and a wider ice complex in the nearshore can act as the equivalent of a temporary shore protection structure, reducing the impact of waves at the coast (Forbes et al., 2002b). On the other hand, ice pressure against the coast, particularly at anomalous high water levels, can lead to severe ride-up or pile-up with potentially devastating consequences for coastal infrastructure. This occurred in New Brunswick and parts of PEI during the storm of 21-22 January 2000, with record high water levels, and again in PEI during a more modest surge event on 17 January 2004 (Figure 3). In the January 2000 event, ice pile-up over dunes, breakwaters, and other structures caused extensive damage to public infrastructure and private homes along more than 50 km of New Brunswick coast (Forbes et al., 2002b; O'Reilly et al., 2003).

There is some evidence to suggest that, with climate warming at high latitude, the thickness and extent of Arctic sea ice is in decline (Johannessen et al., 1999; Vinnikov et al., 1999). With increasing open water fetch in coastal waters, the potential for wave erosion along susceptible Arctic shorelines may be significantly increased (Anisimov et al., 2001; McLean et al., 2001).

In more southern waters with winter sea ice, the trends in ice concentration are less clear. Thirty years of sea-ice records in the Gulf of St. Lawrence show a quasi-periodic variation in seasonal total accumulated ice cover and length of ice season, with a statistically ambiguous trend to less ice in recent years (Forbes et al., 2002b). Some models suggest the potential for complete disappearance of sea ice in the Gulf by the middle of this century (Flato et al., 2000). It is more likely that we will see a continuation of the high inter-annual and inter-decadal variance, with a trend toward more and more 'light-ice' years in future, providing more extensive open water during the winter storm season when prevailing winds are onshore (Forbes et al., 2004b).

2.3 Storms and storm surges

Storms are agents of change in the coastal zone. Much of the impact of climate change is realized through storm activity superimposed on the background of rising relative sea levels, reduced sea ice and increased open-water fetch, among other factors (Forbes et al. 2004b).

Changes in storm intensity and possible changes in storm tracks are probable results of future warming in the tropical Atlantic and eastern North America. These may have a significant impact on the frequency and magnitude of associated storm surges (Thompson et al. 2002), with important implications for the probability of flooding.

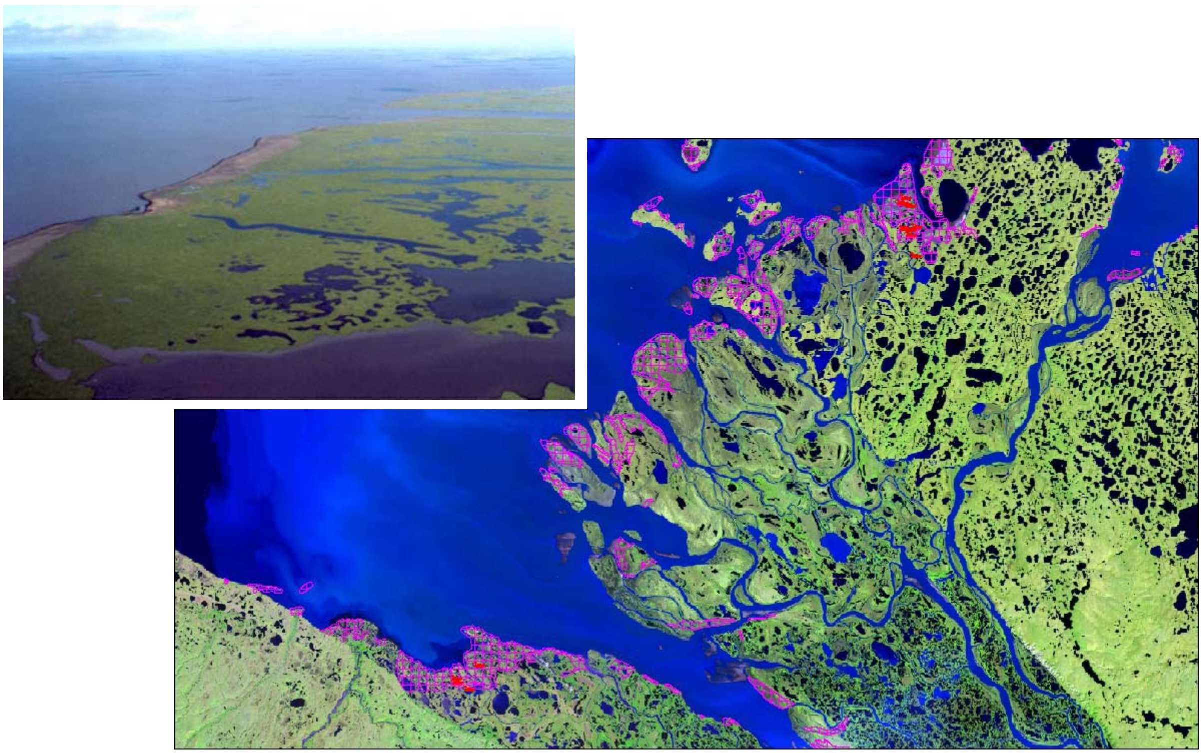

Figure 4. Landsat image of Mackenzie Delta, showing extensive low-lying outer delta plain and (cross-hatched) area flooded in modest early-summer surge in 2002, when many tundra swan nests were destroyed. Inset: Oblique view looking NE along delta front at erosion-monitoring site on Ellice Island (DLF, Geological Survey of Canada, 2002-07-26). Note low scarp cut into organic-rich silts along the ocean shore (Beaufort Sea at left), with fresh silt deposition along the seaward margin of the delta plain. Engineering of hydrocarbon production facilities in this environment will have to adjust for storm-surge flooding with sea-level rise and delta subsidence.

Figure 5. Deeply undercut and collapsed tundra blocks in ice-rich sands, Tuktoyaktuk Island, NWT (courtesy S.M. Solomon, Geological Survey of Canada, 2000-08).

In the Beaufort Sea, where the open-water season is short and the ice-free fetch is limited, 80% of the variance in water levels is due to meteorological effects (Forbes, 1981) and storm-surge heights of 1 to 2 m overwhelm the 0.5 m range of astronomical tides. Maximum storm-surge flooding has been recorded to about 2.5 m above approximate mean water level at Tuktoyaktuk and 2.8 m along part of the Mackenzie Delta front (Forbes and Frobel, 1985; Harper et al., 1988), associated with a major storm in 1970, comparable to another in 1944. Numerous lesser surges cause less extensive flooding, often several times in a season. With slow regional subsidence and relative sea-level rise (Forbes et al., 2004a), the implications for coastal communities such as Tuktoyaktuk, Paulatuk, Sachs Harbour, and Holman cannot be ignored and flooding in the outer Mackenzie Delta is a critical issue for the forthcoming development of natural gas production and pipeline facilities (Figure 4).

Despite the short season and limited wave climate in the western Arctic, storm-wave erosion, combined with thaw of massive ice in coastal exposures, contributes to rapid shoreline recession (Figure 5; Kobayashi et al., 1999). Rates of erosion are correlated with wave energy, storm water level, and ultimately with storm frequency and open-water fetch. A statistical analysis involving a scenario with more open water in a future warm climate (Solomon et al., 1994) concluded that mean annual rates of coastal retreat in future might be comparable to rates of shore erosion documented in exceptionally stormy years in the 1970s to 1980s.

3. ADAPTING TO IMPACTS IN THE COASTAL ZONE

The impacts of rising relative sea level, changes in storm intensity, changes in sea ice and wave energy, and changes in air and ground temperatures may be far-reaching for coastal communities and infrastructure (Figures 6 & 7). Higher flooding, higher wave runup, and accelerated shoreline erosion are among the expected outcomes. A major challenge is to understand the implications of climate variability superimposed on long-term trends in sea level and other environmental factors. As noted earlier, major storms often play a critical role in driving coastal change. Storm clustering may be a key factor, if the time between storms is too short to allow recovery of scarped coastal dunes or other features that would otherwise contribute to natural resilience (Forbes et al., 2004b).

Figure 6. Road setback, Route 132, Bonaventure, QC, showing former highway in foreground (marked by white lines), truncated by gullies intersecting the coastal cliff at right, and present highway (beside power poles), set back further from the coast at left (DLF, Geological Survey of Canada, 2004-05-09).

Adaptation to these changes, including the effects of extreme events, may comprise a variety of tools and strategies, revolving around the concepts of vulnerability, risk awareness, protection against risk, accommodation to risk, avoidance of risk, and enhanced adaptive capacity and resilience (Klein and Nicholls, 1999).

Figure 7. Increasingly large and expensive homes are being built on ocean-front land in many areas. This shows a variety of shore-protection structures at Barachois, NB, where the sand supply is very limited and rapid coastal retreat is the norm (DLF, Geological Survey of Canada, 2002-09). This was also one of the areas badly hit by sea-ice pile-up onshore in January 2000, when ice penetrated into the interior of some homes.

In a recently completed study of climate-change impacts in the coastal zone on Prince Edward Island, a number of specific options were considered (Forbes et al., 2002a). These included hazard identification and monitoring, managed retreat or avoidance, accommodation and enhanced resilience, shore or flood protection, and options involving various aspects of coastal management, including enhanced public education and awareness of hazards. Much of the following material is taken from this report.

3.1 Hazard identification and monitoring

New technology, specifically airborne scanning laser altimetry (LiDAR), has revolutionized our ability to produce high-resolution digital elevation models (DEMs) with high spatial density (order 1 m grid size) and vertical accuracy within 0.3 m (e.g., Webster et al., 2004). It is important to note, however, that LiDAR surveys require extensive ground validation and that production of the DEM is only the first step in flood-risk mapping. Definition of the flooding hazard requires clear specification of vertical datums and detailed statistical analysis of flood levels and probabilities (Thompson et al., 2002), as well as reliable predictions of future changes in relative sea level (see above). LiDAR DEMs are also useful in assessing erosion hazards on exposed coasts, where they can provide extensive data on beach width and slope, dune sand volumes, and location of structures in relation to the shoreline.

Improved tools for predicting rates of shoreline erosion are much needed, and require an aggregated modeling approach to predict changes under highly non-linear conditions over many years. Some of the simpler approaches used in the past (e.g., Bruun, 1962) are inadequate and can provide misleading results. Some progress in large-scale and long-term modeling has been made recently (e.g., de Vriend, 2003; Hanson et al., 2003; Cowell et al., 2003; Leont'yev, 2003) and some efforts have been undertaken to incorporate uncertainty into coastal predictive models (Cowell and Zeng, 2003). However, there remains an urgent need for better predictive tools.

Recognition of changing vulnerability and the need for regular reassessment of risk points to the need for ongoing environmental and coastal monitoring. The Geological Survey of Canada maintains a widespread network of shoreline monitoring sites in collaboration with provincial and other partners. These provide ground control for more extensive estimates of coastal change from airphotos and, increasingly, from new high-resolution (<1 m pixel) satellite imagery.

3.2 Managed retreat or avoidance

The most direct form of avoidance in many parts of Canada is to restrict development or to enforce strict setback requirements in vulnerable locations. This is less applicable where extensive development has already taken place. In the Parks Canada system, it is recognized that minimizing development of infrastructure in erosion-prone locations is more cost-effective and consistent with ecological integrity objectives than previous policies involving protection. Land swapping may be another public policy option, which has some history of use in Prince Edward Island (Forbes et al., 2002a). Coastal setback is a widely used measure in municipal zoning and provincial coastal policies, but selection of an appropriate setback distance and appropriate enforcement are challenges. Selection of the setback on the basis of a fixed distance may be less helpful than basing the choice on a time interval, but this implies the ability to predict erosion rates into the future. Extrapolation of historical rates may not be appropriate and the validity of the historical rates adopted may be questionable (Crowell et al., 1991; Dolan et al., 1991). If the setback is defined in terms of a time interval and the potential for significant increase in erosion rates with climate change is not incorporated into the calculations, then the intended factor of safety may not be achieved.

3.3 Accommodation and enhanced resilience

Accommodation options for flooding may include flood-proofing of basements and other measures to reduce damage, raising foundation heights or the heights of protective structures, wharves, and other coastal infrastructure. Substitution of bridges in place of causeways is being pursued in some places, but can become a complicated issue because of changes that may have occurred since the causeway was built.

Enhanced resilience of natural coastlines is a potentially cost-effective strategy being promoted in some areas. Any opportunities taken to strengthen the resilience of dune buffers, salt marshes and other natural systems may pay dividends in reduced future impacts and economic losses. Pressures for coastal development and ocean-front construction are straining the natural systems in many places.

3.4 Protection

Shore protection can be very costly and have limited endurance in some settings. Therefore, it is often worthwhile to consider other options before embarking on a protection project. There are, however, situations in which hard or soft protection is required and justified for specific high-value properties, heritage structures, or other amenities. In such cases, it may be preferable to adopt soft protection measures such as beach nourishment or dune restoration before resorting to hard structural solutions.

If seawalls or revetments are deemed appropriate, they should be designed to accommodate changes in sea level, wave climate, and other effects of future climate change. The need for future maintenance and the long-term feasibility of 'holding the line' should be considered at the outset. It is important to recognize that coastal protection structures may alter the coastal dynamics and careful consideration of the entire relevant coastal system is required in selecting the location and design of protection. An important concern is the need to provide for landward migration of coastal wetlands as the sea level rises and the coast retreats. Hard structures that prevent such migration can result in 'coastal squeeze', wherein the area of salt marsh is dramatically reduced as the seaward margin moves landward and the landward margin is held in place.

3.5 Coastal management

Integrated management and planning in the coastal zone needs to take a holistic approach to the coastal system, incorporating both terrestrial and marine components. While specific initiatives have been undertaken at federal, provincial, and municipal levels in some jurisdictions, and the importance of adopting natural boundaries such as watersheds is more widely recognized, it may be worthwhile to consider opportunities for development of coastal management plans corresponding to natural coastal cells, in a manner similar to the Shore Management Plans in England and Wales. An important aspect of such plans is the recognition that they require frequent revision to reflect evolving policy, understanding, and innovation, as well as changes in the coastal system itself (Leafe et al., 1998). In the USA, some initiatives of this kind have been encouraged by the insurance industry and have taken the form of 'showcase communities' or counties (Heinz Center, 2000). In any case, it is important to move beyond past approaches that resulted usually in piecemeal efforts with inconsistent results and sometimes unintended consequences. A philosophy of managing the coastal system rather than protecting individual properties, and a planning framework that supports such an approach are desirable objectives.

4. CONCLUSIONS

Many parts of the coast of Canada are sensitive to future climate changes and their effects, including accelerated sea-level rise and changes in storms, sea ice, wave climate, temperatures, and other factors. New technologies and approaches provide opportunities to adopt enlightened strategies to enhance adaptive capacity, strengthen natural and societal resilience, and reduce the vulnerability of communities and infrastructure. These efforts should result in reduced impacts and limited losses, but require sound scientific knowledge and improved predictive capacity to ensure an adequate understanding of future hazards and risks on the part of residents, community leaders, and other stakeholders.

4.1 Acknowledgements

This paper is based on a number of reviews and case studies undertaken over the past few years in Canada and overseas and I am indebted to the many colleagues who have helped to provide a growing understanding of climate-change impacts and adaptation strategies in the coastal zone. This work is supported under the *Program on Reducing Canada's Vulnerability to Climate Change* in the Earth Sciences Sector of Natural Resources Canada. Marie-Claude Williamson very kindly provided linguistic advice with the Résumé. Discussions with Goerge Parkes, Charles O'Reilly, Keith Thompson, Gavin Manson, Dominique Bérubé, Armand Robichaud, Kathryn Parlee, Mike Craymer and many others were helpful in developing the ideas presented here. Comments by Bob Taylor and Steve Solomon on a draft of the paper are greatly appreciated.

5. REFERENCES

Andrews, J.T. 1989. Postglacial emergence and submergence. *In* Quaternary Geology of Canada and Greenland, Chapter 8. *Edited by* R.J. Fulton. Geology of Canada, volume 1. Geological Survey of Canada, Ottawa, pp. 546-562.

Anisimov, O., Fitzharris, B., Hagen, J.O., Jefferies, R., Marchant, H., Nelson, F., Prowse, T., and Vaughan, D.G. 2001. Polar regions (Arctic and Antarctic). *In* Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II, Third Assessment Report, Intergovernmental Panel on Climate Change. *Edited by* J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White. Cambridge University Press, Cambridge UK and New York USA, pp. 801-841.

Bruun, P. 1962. Sea-level rise as a cause of shore erosion. Journal of Waterways and Harbors Division ASCE, **88**: 117-130.

Church, J.A., Gregory, J.M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M.T., Qin, D. and Woodworth, P.L. 2001. Changes in sea level. *In* Climate Change 2001: The Scientific Basis. Contribution of Working Group I, Third Assessment Report, Intergovernmental Panel on Climate Change. *Edited by* J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P. van der Linden, X. Dai, K. Maskell and C.I. Johnson. Cambridge University Press, Cambridge UK and New York USA, pp. 639-693.

Cowell, P.J. and Zeng, T.Q. 2003. Integrating uncertainty theories with GIS for modeling coastal hazards of climate change. Marine Geodesy, **26**: 5-18.

Cowell, P.J., Stive, M.J.F., Niedoroda, A.W., de Vriend, H.J., Swift, D.J.P., Kaminsky, G.M. and Capobianco, M. 2003. The coastal tract (Part 1): a conceptual approach to aggregated modeling of low-order coastal change. Journal of Coastal Research, **19**: 812-827.

Crowell, M., Leatherman, S.P. and Buckley, M.K. 1991. Historical shoreline change: error analysis and mapping accuracy. Journal of Coastal Research, **7**: 839-852.

De Vriend, H. 2003. On the prediction of aggregated-scale coastal evolution. Journal of Coastal Research, **19**: 757-759.

Dolan, R., Fenster, M.S. and Holme, S.J. 1991. Temporal analysis of shoreline recession and accretion. Journal of Coastal Research, **7**: 723-744.

Douglas, B.C. and Peltier, W.R. 2002. The puzzle of global sea-level rise. Physics Today, **55**: 35-40.

Dyke, A.S. and Peltier, W.R. 2000. Forms, response times and variability of relative sea-level curves, glaciated North America. Geomorphology, **32**: 315-333.

Flato, G.M., Boer, G.J., Lee, W.G., McFarlane, N.A., Ramsden, D., Reader, M.C. and Weaver, A.J. 2000.

The Canadian Centre for Climate Modelling and Analysis global coupled model and its climate. Climate Dynamics **16**: 451–467.
Forbes, D.L. 1981. Babbage River delta and lagoon: hydrology and sedimentology of an Arctic estuarine system. PhD dissertation, University of British Columbia, Vancouver, 554 pp.
Forbes, D.L. and Frobel, D. 1985. Coastal erosion and sedimentation in the Canadian Beaufort Sea. Geological Survey of Canada, Paper 85-1B: 69-80.
Forbes, D.L. and Taylor, R.B. 1994. Ice in the shore zone and the geomorphology of cold coasts. Progress in Physical Geography, **18**: 59-89.
Forbes, D.L., Shaw, R.J. and Manson, G.K. 2002a. Adaptation. *In* Coastal Impacts of Climate Change and Sea-Level Rise on Prince Edward Island, *Edited by* D.L. Forbes and R.W. Shaw. Geological Survey of Canada, Open File 4261, Supporting Document 11, 18 pp. (on CD-ROM).
Forbes, D.L., Manson, G.K., Chagnon, R., Solomon, S.M., van der Sanden, J.J. and Lynds, T.L. 2002b. Nearshore ice and climate change in the southern Gulf of St. Lawrence. International Symposium on Ice in the Environment, IAHR, Dunedin, New Zealand, pp. 318-326.
Forbes, D.L., Craymer, M., Manson, G.K. and Solomon, S.M. 2004a. Defining limits of submergence and potential for rapid coastal change in the Canadian Arctic. Berichte zur Polar- und Meeresforschung, *in press*.
Forbes, D.L., Parkes, G.S., Manson, G.K. and Ketch, L.A. 2004b. Storms and shoreline erosion in the southern Gulf of St. Lawrence. Marine Geology, *in press*.
Hanson, H., Aarninkhof, S., Capobianco, M., Jiminez, J.A., Larson, M., Nicholls, R.J., Plant, N.G., Southgate, H.N., Steetzel, H.J., Stive, M.J.F. and de Vriend, H.J. 2003. Modeling of coastal evolution on yearly to decadal time scale. Journal of Coastal Research, **19**: 790-811.
Harper, J.R., Henry, R.F. and Stewart, G.G. 1988. Maximum storm surge elevations in the Tuktoyaktuk region of the Canadian Beaufort Sea. Arctic, **41**: 48-52.
Heinz, H. John III, Center for Science, Economics and the Environment. 2000. The Hidden Costs of Coastal Hazards: Implications for Risk Assessment and Mitigation. Island Press, Washington, DC, 220 pp.
Johannessen, O.M., Shalina, E.V., and Miles, M.W. 1999. Satellite evidence for an Arctic sea ice cover transformation. Science, **286**: 193-195.
Klein, J.T. & Nicholls, R.J. 1999. Assessment of coastal vulnerability to climate change. Ambio, **28**: 182-187
Kobayashi, N., Vidrine, J.C., Nairn, R.B. and Solomon, S.M. 1999. Erosion of frozen cliffs due to storm surge on Beaufort Sea coast. Journal of Coastal Research, **15**: 332-344.
Leafe, R., Pethick, J. and Townsend, I. 1998. Realising the benefits of shoreline management. Geographical Journal, **164**: 282-290.
Leont'yev, I.O. 2003. Modeling erosion of sedimentary coasts in the western Russian Arctic. Coastal Engineering, **47**: 413-429.
McLean, R.F., Tsyban, A., Burkett, V., Codignotto, J.O., Forbes, D.L., Mimura, N., Beamish, R.J. and Ittekkot, V. 2001. Coastal zones and marine ecosystems. *In* Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II, Third Assessment Report, Intergovernmental Panel on Climate Change. *Edited by* J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White. Cambridge University Press, Cambridge UK and New York USA, pp. 341-379.
Mitrovica, J.X., Tamislea, M.E., Davis, J.L., and Milne, G.A. 2001. Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. Nature, **409**: 1026-1029.
O'Reilly, C.T., Forbes, D.L. and Parkes, G.S. 2003. Mitigation of coastal hazards: adaptation to rising sea levels, storm surges and shoreline erosion. Proceedings, First Coastal, Estuary and Offshore Engineering Specialty Conference, Canadian Society for Civil Engineering, Moncton, CSN-410, pp. 1-10.
Parkes, G.S., Forbes, D.L., and Ketch, L.A. 2002. Sea-level rise. *In* Coastal Impacts of Climate Change and Sea-Level Rise on Prince Edward Island, *Edited by* D.L. Forbes and R.W. Shaw. Geological Survey of Canada, Open File 4261, Supporting Document 1, 33 pp. and 5 attachments (on CD-ROM).
Peltier, W.R. 2004. Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2) model and GRACE. Annual Review of Earth and Planetary Sciences, **32**: 111-149.
Shaw, J., Taylor, R.B., Solomon, S., Christian, H.A., and Forbes, D.L. 1998. Potential impacts of global sea-level rise on Canadian coasts. Canadian Geographer, **42**: 365-379.
Solomon, S.M., Forbes, D.L. and Kierstead, B. 1994. Coastal impacts of climate change: Beaufort Sea erosion study. Environment Canada, Downsview. Canadian Climate Centre, Report 94-2, 34 pp.
Solomon, S.M., Forbes, D.L. and Manson, G.K. 2004. Geological conditions in the coastal-nearshore region of the Mackenzie Delta: implications for development. *These proceedings*.
Thompson, K., Ritchie, H., Bernier, N.B., Bobanovic, J., Desjardins, S., Pellerin, P., Blanchard, W., Smith, B. and Parkes, G. 2002. Modelling storm surges and flooding risk at Charlottetown. *In* Coastal Impacts of Climate Change and Sea-Level Rise on Prince Edward Island, *Edited by* D.L. Forbes and R.W. Shaw. Geological Survey of Canada, Open File 4261, Supporting Document 6, 48 pp. (on CD-ROM).
Vinnikov, K.Y., Robock, A., Stouffer, R.J., Walsh, J.E., Parkinson, C.L., Cavalieri, D.J., Mitchell, J.F.B., Garrett, D., and Zakharov, V.F. 1999. Global warming and Northern Hemisphere sea ice extent. Science, **286**: 1934-1937.
Webster, T.L., Forbes, D.L., Dickie, S. and Shreenan, R. 2004. Using topographic lidar to map flood risk from storm-surge events for Charlottetown, Prince Edward Island, Canada. Canadian Journal of Remote Sensing, **30**: 64-76.