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NUCLEAR WASTE MANAGEMENT ORGANIZATION

SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

NWMO BACKGROUND PAPERS
4. SCIENCE AND ENVIRONMENT

4-5 REVIEW OF THE POSSIBLE IMPLICATIONS OF CLIMATE CHANGE ON THE LONG-TERM MANAGEMENT OF SPENT NUCLEAR FUEL

Gordon A. McBean

NWMO Background Papers

NWMO has commissioned a series of background papers which present concepts and contextual information about the state of our knowledge on important topics related to the management of radioactive waste. The intent of these background papers is to provide input to defining possible approaches for the long-term management of used nuclear fuel and to contribute to an informed dialogue with the public and other stakeholders. The papers currently available are posted on NWMO's web site. Additional papers may be commissioned.

The topics of the background papers can be classified under the following broad headings:

1. **Guiding Concepts –** describe key concepts which can help guide an informed dialogue with the public and other stakeholders on the topic of radioactive waste management. They include perspectives on risk, security, the precautionary approach, adaptive management, traditional knowledge and sustainable development.
2. **Social and Ethical Dimensions** - provide perspectives on the social and ethical dimensions of radioactive waste management. They include background papers prepared for roundtable discussions.
3. **Health and Safety –** provide information on the status of relevant research, technologies, standards and procedures to reduce radiation and security risk associated with radioactive waste management.
4. **Science and Environment –** provide information on the current status of relevant research on ecosystem processes and environmental management issues. They include descriptions of the current efforts, as well as the status of research into our understanding of the biosphere and geosphere.
5. **Economic Factors** - provide insight into the economic factors and financial requirements for the long-term management of used nuclear fuel.
6. **Technical Methods** - provide general descriptions of the three methods for the long-term management of used nuclear fuel as defined in the NFWA, as well as other possible methods and related system requirements.
7. **Institutions and Governance** - outline the current relevant legal, administrative and institutional requirements that may be applicable to the long-term management of spent nuclear fuel in Canada, including legislation, regulations, guidelines, protocols, directives, policies and procedures of various jurisdictions.

REVIEW OF THE POSSIBLE IMPLICATIONS OF CLIMATE CHANGE ON THE LONG-TERM MANAGEMENT OF SPENT NUCLEAR FUEL

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EXECUTIVE SUMMARY

Climate and weather are basic characteristics of Canada and they impact almost everything. There is now strong evidence that the climate is changing and will change at an accelerating rate in the coming century. Despite international efforts through the UN Framework Convention on Climate Change, it is unlikely that atmospheric greenhouse gas concentrations will be stabilized within the next two hundred years. Stabilization of climate will only come after that while the full effects of sea level rise will take further hundreds of years to materialize. Changing climate will bring with it more intense precipitation events, severe winter storms and stronger hurricanes. Lake levels will likely fall while the sea level rises. Groundwater will be impacted through more frequent droughts interspersed with intense rain events. There is a risk of more tornadoes. These weather events will have impacts on all structures and transportation systems in Canada (and around the globe). Risks to above ground storage and transportation facilities for spent nuclear fuels will come from extreme wind and precipitation events. Near-surface, belowground storage will be at risk from effects of changing ground characteristics, mainly hydrologic but also thermal. If ships are used for transportation of spent fuels, the lowering of the Great Lakes will impact on vessel capacity. Sea level rise will impact the facilities at Point Lepreau. These risks will increase over the next few hundred years, requiring comprehensive risk and adaptive management strategies.

Over the next several hundred years, climate could stabilize but in the interim there are risks of rapid climatic changes or discontinuities. These risks become more likely if emissions of greenhouse gases continue at high levels and push the climate system far from that of the past few thousand years. Model studies indicate that the onset of the next ice age will be delayed to beyond the next 10,000 years but it will inevitably come with major impacts on any surface facilities and risks to deep geological disposal.

Climate change is a reality and it brings risks that must be factored into the long-term management of spent nuclear fuel. The scientific basis for the risk analysis is available and with an adaptive management approach, the new knowledge can be factored in as the decades pass.

TABLE OF CONTENTS

1. INTRODUCTION

Canadians talk about the weather; our lives are affected by it and it helps to mould our culture and identity. Weather and climate, which is really the collective description of weather, can be benevolent; it can also be life threatening and destructive. The twelve Canadians who lost their lives in a matter of minutes when a tornado struck Pine Lake Alberta in 2000 and the twelve others who were killed in the Barrie, Ontario tornado of 1985 are part of the tragic legacy of our weather. So is the $5.5B spent by Canadians and their governments in recovering from the 1998 ice storm. When Canadians carry out their daily lives and when they construct their buildings, and drive their cars, they factor in the weather. And we now have evidence that the weather and climate that we have become accustomed to, is changing; our climate is changing and will continue to change at a greater rate in the decades to come.

This paper reviews the possible implications of climate change on the long-term management of spent nuclear fuel in Canada. As the climate changes and with it, the characteristics of day-to-day weather, the risks of impacts on storage and disposal facilities and transportation systems will change. The objective of this paper is to assess the changes in the risks on the management of spent nuclear fuel, due to changes brought on by the waste (the carbon dioxide emissions) of fossil fuel use.

Weather and climate have always had major impacts on societies. Over the past thousands of years in the development of civilizations, there have been impacts of climate change or variations that have led to the development and collapse of civilizations[1]. Examples include the productive climate in the seat of modern civilization in Iraq and the changes that caused out migration, Egypt and the eastern Sahara desert changing from the "bread basket" of that part of the world and the collapse of the Egyptian civilization; the productive climate in the US south west and the subsequent drying causing the out migration of Indian tribes; the warming that allowed the Vikings to colonize Greenland and the subsequent cooling that caused their colonies to collapse. Natural climatic shifts have had profound effects on cultures and civilizations. Today, our global civilization is facing a period of projected rapid human-induced climate change. This will have impacts on all aspects of our society, our governance and our future evolution as peoples of this Earth. Within this framework, the long-term management of spent fuel, which will require the maintenance of stable governance structures over long periods of time, will have to be done. As has been demonstrated in the past, maintaining the governance structures required for the long term challenge, in the face of ever increasing rates of climate change and resulting inevitable social disruption and shifts in societal priorities, will not be an easy task. Social change and climate change will be inextricably linked over the decades to come. For at least the next half-century, there will be operating nuclear power reactors and spent fuel in storage. During the following half-century, this fuel will either be being placed in long-term storage or being disposed. Whatever management concept is chosen, it will be expected to last for a long period, 10s of thousands of years.

Like everything else, the full range of nuclear-power facilities, from mining processes, reactors and storage sites to the transportation systems that connect them, are influenced by weather and climate. They need to be designed, constructed, maintained and operated in ways that make the risks from weather exceedingly small. The management of nuclear power facilities has presumably incorporated our weather and climate in their plans and actions. But now climate and weather are changing. Because of the long-term nature of the management of spent nuclear fuels, there is the need to take a very long-term view of how climate will change, on a horizon to 10,000 (or more) years in the future. Although not the topic of this paper, there will be implications of climate change on social change and governance and their implications for the management of spent nuclear fuel on this same time period.

Section 2 of this paper introduces the relationships between climate change and the storage of spent nuclear fuel. Section 3 provides background as to how and why climate change became an international issue and describes the response of the global community, the United Nations Framework Convention on Climate Change. Section 4 will describe Earth's weather and climate and how they are predicted. Section 5 looks at the next 100 years, for which there is reasonable basis for projections of climate change. In this section, the stimuli or hazards leading to vulnerabilities, in this case, the key climate-related events, are discussed. In section 6, the scenarios of Section 5 are extended further into the future, recognizing the increasing uncertainty and the possibility of surprises, abrupt changes and/or irreversible events. Beyond the next few hundred years, climate projections must be based mainly on understanding the dominant factors that have caused past climate variability and changes, in particular the orbital characteristics of planet Earth as it revolves around the Sun. Section 7 will look ahead 10,000 years. This review will end with a Summary (Section 8).

2. CLIMATE CHANGE AND SPENT NUCLEAR FUEL

Climate change has been identified as one of the major challenges changing the global community. Runnalls[2], President of the Canadian International Institute for Sustainable Development, notes that *"…climate change, (is) the greatest problem facing sustainable development today."* Sustainable development is development that meets the needs of the people today without compromising the ability of future generations to meet their own needs. Climate change is one of the global problems that require a long-term perspective, as is management of spent nuclear fuel[3]. Runnalls laid out criteria for building a Nuclear Waste Management Organization (NWMO) sustainable development strategy including considerations of the environment and risk assessment. This paper deals with both those issues. First, a changing environment (its climate) may have impacts on the long-term management of spent nuclear fuel, with the possibility that the resulting leaks from storage will have impacts on the environment. Second, the complexities of the climate system and the uncertainties regarding human actions in response to climate change make projections over an extended period of time necessarily uncertain, making a risk assessment approach appropriate. The climate events of most concern are the extreme and relatively rare events, such as tornadoes, hurricanes, and severe winter storms. Changes in the characteristics of these events, which will be the emphasis of this review, are even more difficult to predict than changes in average conditions. For longer periods, the risk of major changes in groundwater and possible glaciations also become important.

Presently, all Canadian spent nuclear fuel is stored on reactor sites, either in wet or dry storage[4]. About 89% of the fuel is stored at sites along Lakes Ontario (at Pickering and Darlington) and Huron (at Bruce) in southern Ontario. These sites are right along the lakeshore. A further 6% is located at Point Lepreau, about 40 km west of Saint John, New Brunswick, along the shores of the Bay of Fundy. Another 5% is located on the south shore of the St. Lawrence River, 15 km east of Trois Rivieres, Quebec. There are small amounts in southeastern Manitoba at Whiteshell and northeastern Ontario at Chalk River. When spent fuel is removed from the reactor, it continues to produce intense gamma radiation and heat. Current practice in Canada is to allow spent fuel to cool in water-filled bays for ten years or more. The used fuel can then be economically and safely transferred into aboveground dry storage containers for extended interim storage at each reactor site. It is expected that these dry storage containers will be used for 50 years or more. Decisions on long-term management have not yet been taken. The Seaborn Report, submitted to the federal Minister of the Environment and Minister of Natural Resources in November 1998, said that "*the concept of deep geological disposal had been, on balance, adequately demonstrated from a technical perspective but, from a social perspective, it had not.*"[5]

This paper assumes that the principal four components of possible management concepts that may be influenced to a greater or lesser extent by the impacts of a changing climate are: 1) reactor site storage of used nuclear fuel either above ground or below ground; 2) centralized storage of used nuclear fuel either above ground or below ground; 3) disposal of used nuclear fuel in a deep geological repository; and 4) transportation systems and the movement of used nuclear fuel from reactor sites to a centralized storage facility or deep geological repository. In view of the present distribution of reactor sites and spent nuclear fuel in Canada and that the Canadian Shield is a likely site for deep geological disposal, this review of climatic changes focuses on non-Arctic Canada and on the eastern half of the country (east of the Manitoba-Saskatchewan border).

In considering climate change and long-term management of spent nuclear fuel, it is appropriate to bring in the ideas of vulnerability and adaptive capacity, as developed in climate change, natural hazards and other fields[6]. Vulnerability refers to the susceptibility for harm in a system relative to a stimulus (or stimuli) and depends on exposure and adaptive capacity to deal with the stimulus. An alternate but consistent approach is that discussed by Leiss[7] where the notion of risk is considered as a prediction or expectation, and then called *risk estimation*. This "*involves the following factors:*

- *a hazard (the source of danger),*
- *exposure to the hazard (at a certain dose),*
- *uncertainty of occurrence and outcomes (expressed by the probability or chance of occurrence),*
- *adverse consequences (the possible outcomes),*
- *a time frame for evaluation, and*
- *the perspectives of those affected about what is important to them*."

Vulnerability results when hazards intersect with exposures and there is an element of uncertainty. The notion of adaptive capacity is included in the sense of ability to change exposure and also in changing the adverse consequences when the hazard and exposure coincide. Lee[8] defines adaptive management as *"the process of conceiving and carrying* *out a program as an experiment, so that learning from experience becomes an explicit objective. An adaptive approach to nuclear waste management may enable NWMO to build and sustain public trust while accelerating technical progress."*

How will vulnerability change in the future as the climate changes? Present storage facilities have been designed and managed to accommodate the present climate-related vulnerabilities according to present building codes, as are the designs of all buildings and housing. These building codes are, unfortunately, largely based on past weather and do not incorporate projections of the future. In the case of nuclear facilities, they must also meet the construction licensing requirements of the Canadian Nuclear Safety Commission, which requires that factors associated with climate change be assessed and incorporated into the design.

Hence, if the climate does not change then the climate-related vulnerabilities do not change vis-à-vis present storage and transportation systems. Adaptive management and use of adaptive capacities – ways of changing the storage facilities – so that the vulnerabilities do not increase as the climate changes, would be consistent with the approach recommended by Lee. Since the present on-site dry storage systems are designed for about 50+ years of use, decisions on their replacement can be made with additional years of knowledge about climate change – learn from experience. There is the need to take initial decisions to respond to climate change but they can then be modified as time and knowledge move on. There may, of course, be other reasons, such as security or responding to concerns of the local host communities, for changing the storage system at an earlier time. The precautionary principle, to be discussed, needs also to be part of the management strategy.

3. CLIMATE SCIENCE LEADING TO THE UNITED NATIONS CLIMATE CONVENTION

Concerns about future climate change, as a result of human activities enhancing the natural greenhouse effect and increasing the Earth's temperature, are about 180 years old. Jean-Baptiste-Joseph Fourier, a well-known French mathematician, first postulated the link between the greenhouse effect, carbon dioxide (CO_2) as a major greenhouse gas (GHG) and the Earth's temperature, in 1824[9]. It is now known that the natural greenhouse effect, due to the presence in the atmosphere of greenhouse gases, leads to warming the global mean temperature about 30^{o}C. The Swedish Nobel Laureate, Svante Arrhenius, drew upon this to develop, in 1896, the first theoretical model of how atmospheric CO_2 affects the Earth's temperature and how doubling its concentration would lead to global warming. The first systematic direct measurements of global mean CO_2 concentrations were started during the International Geophysical Year of 1957; even then values were found to be considerably higher than some earlier measurements, indicative of pre-Industrial Revolution values. In 1957, Roger Revelle and Hans Suess[10] of the Scripps Institute of Oceanography argued that the oceans could not absorb the human emissions of CO_2 as fast as they were being produced. They noted that this would leave the human-released CO_2 in the atmosphere for centuries and stated: *"Human beings are now carrying out a large-scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future."* They further stated, *"We are returning to the atmosphere and oceans the concentrated organic carbon stored in the* *sedimentary rocks over hundreds of millions of years."* Scientific analyses of air bubbles trapped in ice cores, obtained by drilling deep into the Antarctic and Greenland ice sheets, have provided histories of atmospheric CO_2 (and other GHG, aerosols, etc) over the past 400,000 years. Analysis of the isotopic composition of the ice itself gives a measure of global mean temperature. These remarkable analyses have shown a regular cycle of ice ages (glaciations) and warm periods (interglacials or deglaciations), with global mean temperatures varying from near present values (we are now in a warm or interglacial period) to about 5-7^{o}C colder during the ice ages. There also seems to be upper and lower bounds on CO_2 concentrations: varying between 180 (at the height of the ice age) and 300 ppmv (parts per million by volume of CO_2 in air) during interglacials[11].

By the early 1980s, the issue of climate change began to move from scientific to policy agendas. On the international scene, there were a series of meetings and reports of which the 1985 Second Joint UNEP/ICSU/WMO[12] International Assessment of the Role of Carbon Dioxide and other Greenhouse Gases in Climate Variations and Associated Impacts was particularly important. Three years later, in 1988, the WMO and UNEP created the Intergovernmental Panel on Climate Change[13], to provide authoritative assessments of climate science, impacts and adaptations and response strategies. The IPCC has played the role of providing policy-relevant but not policy prescriptive scientific advice.

The first three assessment reports of the IPCC (in 1990, 1995, 2001) have provided the evidence for climate change. The next planned IPCC assessment is to be completed in 2007. The strength of the arguments for detection and attribution of human-induced climate change and the scientific basis for projections into the future have greatly increased over this period. Atmospheric measurements and analysis of ice cores and other indicators of past climates have shown that, over the past 250 years, the atmospheric CO_2 concentration has risen 31% (to 368 ppmv in 2000), a value unprecedented in the last 400,000 years[14]. The current rate of increase is unprecedented during at least the past 20,000 years. About three-quarters of the anthropogenic CO_2 emissions to the atmosphere during the past 20 years is due to fossil fuel burning. The rest is due to land-use change, especially deforestation. Currently the ocean and the land together are taking up about half of the anthropogenic CO_2 emissions. Over the same period, the atmospheric methane concentrations have increased 151% while those of nitrous oxide have increased by 17%. Although the Global Warming Potentials (GWP, the relative influence of a greenhouse gas, compared to carbon dioxide, over a 100-y horizon, or any other time horizon) for methane is 23 and nitrous oxide, 296, their relative concentrations in the atmosphere are small, making carbon dioxide over 3 times more important as methane and almost 10 times more important than nitrous oxide. Through the GWP, influences of various greenhouse gases can be compared and converted into carbon-dioxide equivalents.

As human activities have released additional CO_2 into the atmosphere, the atmospheric concentration has increased. Since the processes to remove CO_2 from the atmosphere are slow, the atmospheric concentration adjusts slowly to changes in emissions. The climate system itself also adjusts slowly to the changing CO_2 concentration. The result is a lagged response, by more than 100 years, of the climate system to changes in emissions.

There is now a strong body of evidence that there has been a real and substantial change in the global mean temperatures in the 20th century and the values are higher than any for the past 600-1000 years that have been inferred from proxy indicators, such as glacial ice cores and tree rings. Over the 20th century, the globally-averaged surface air temperature has increased by 0.6±0.2 °C[15]. A U.S. National Research Council report, published in 2000, has reaffirmed the validity of the global surface temperature record and its change, while a second National Research Council report affirmed that, in the opinion of the eminent scholars of the panel (all members of the U.S. National Academy of Sciences), the IPCC report was a proper consensus of scientific opinion and that the IPCC process had been appropriate[16]. Human activities are now, without question, changing the concentrations of greenhouse gases (GHG) in the atmosphere. The IPCC[17] concluded that:

"*There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities*".

With publication of the IPCC First Assessment Report in 1990, negotiations moved ahead within the international community towards a climate change convention. At the Earth Summit in Rio in 1992, the United Nations Framework Convention on Climate Change (UNFCCC)[18] was endorsed and a total of 188 countries, including Canada and the United States, have ratified it. The UNFCCC included, as a general statement, that developed countries would aim to reduce their greenhouse gas emissions to 1990 levels by year 2000. Generally, this did not happen. The Goal of the Convention was enunciated in Article 2:

" ... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure food production is not threatened and to enable economic development to proceed in a sustainable manner."

Because of the slow removal processes of greenhouse gases from the atmosphere and its resulting long residence time, reductions in emissions to less than 50% of 1990 levels will be required in order to stabilize the atmospheric concentrations. This is unlikely to be achieved in this coming century. Once stabilization has been reached, a further lag of more than 100 years will be required before the climate stabilizes at a new equilibrium[19].

Nations agreed (Article 3) to protect the climate system and also recognized that they had *"their common but differentiated responsibilities"*. An important principle in the context of this paper was agreement to take precautionary measures; "*… lack of full scientific certainty should not be used as a reason for postponing actions*". Ten years later, in Johannesburg, countries at the World Summit on Sustainable Development agreed to "*Promote and improve science-based decision-making and reaffirm the precautionary principle ..."* The wording was modified to: "*In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, the lack of scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation*." The addition of the phrase *"cost-effective"* does add an economic measure. In many cases it may not be possible to ascertain the "costeffectiveness" of a measure, which could lead to reluctance to use the precautionary principle.

The Convention allocated responsibilities differently to three groups of nations. Annex I Parties (the European Union, economies in transitions (EIT) and others including Australia, Canada, Iceland, Japan, New Zealand, and United States) agreed to undertake emission reduction targets in the first stages of the Convention. Annex II parties (Annex I parties but excluding the EIT) undertook financial commitments with respect to implementation of the Convention processes. All other countries, called non-Annex I countries, do not have obligations in the first stage. The Convention is implemented formally by agreements at Conferences of the Parties (CoP), the first being held in Berlin in 1995. The Geneva Declaration (from CoP 2, in 1996) stated that the science, based on the IPCC Second Assessment Report (1995), was good enough for action. CoP 3 was held in Kyoto in 1997 and agreed to the Kyoto Protocol of the Convention. The Kyoto Protocol overall target was that: *"The Parties included in Annex I shall…ensure that their aggregate anthropogenic carbon dioxide equivalent emissions…do not exceed their assigned amounts… with a view to reducing their overall emissions… by at least 5% below 1990 levels in the commitment period 2008 - 2012."* And that "*Each Party…shall, by 2005, have made demonstrable progress…"* Some specific targets (all compared to 1990 levels) are: EU, 8% reduction; US, 7% reduction; Canada, 6% reduction; Japan, 6% reduction; New Zealand, 0% (meet 1990 level); Russian Federation, 0%; Australia, 8% increase; and Iceland, 10% increase. To meet their targets, countries can use the Kyoto Protocol mechanisms: International Emissions Trading amongst developed countries; Joint Implementation, which give credits for investing in developed countries; the Clean Development Mechanism which give credits for investing in developing countries; and carbon sinks, through management of forestry and agriculture, to help meet their targets.

Entry into force of the Protocol requires ratification by 55 Parties who represent at least 55% of 1990 Annex I emissions. As of January 2004, 120 countries have ratified but their missions total is only 44.2% of the Annex I total. The United States and Australia have declared that they will not ratify the Protocol, so Russia, which has not formally made a decision, holds the deciding vote, since only their 17.4% can put the total to above 55%[20].

Although the Climate Convention does lay a basis for addressing the very long-term perspective, the Kyoto Protocol has a short-term time horizon: to address current greenhouse gas emissions by developed countries within a two-decade time frame, while not including emissions from major developing countries. In his discussion of integrated 1000-year planning, Tonn[21] notes that short time horizons can *"constrain if not completely mask the recognition of big picture issues and threats. For example, over the next ten years, oil supplies may be manageable; over 1000 years, oil supplies and those of natural gas will probably be completely exhausted, thereby threatening the world's economic and political stability if a plan is not in place to develop substitutes for these fossil fuels*[22]*. Over the next 50 years, rising sea levels may not be devastating, but within 1000 years, large swaths of countries like Bangladesh will most certainly disappear*[23]*. Humanity must be prepared to deal with climate change induced human tragedies, as the window to prevent global warming has now closed.*

At this point, it is not enough to reduce the emissions of GHGs through more rational energy policies. The message I take from the IPCC report is that the buildup of GHGs in the atmosphere is already too great to stave off global warming."

This view echoes that of Dr. R. Watson[24], then Chair of IPCC, speaking to the CoP6, who summarized the consensus of most scientists:

"The overwhelming majority of scientific experts, whilst recognizing that scientific uncertainties exist, nonetheless believe that human-induced climate change is inevitable."

4. PREDICTION OF THE EARTH'S WEATHER AND CLIMATE

The Earth's climate varies on a vast range of time scales. Short-time scale variations are called weather. Sunny days or storms, high or low temperatures, light or strong winds – these are elements of weather. Each day Canadians listen to weather forecasts[25], predictions of sequences of weather events, such as: rain this afternoon, followed by clearing overnight, with increasing cloudiness tomorrow morning, with a temperature high today of 10^{o}C, low tonight of 0^{o}C and a high tomorrow of 6^{o}C. Weather forecasts now provide information for the next 5 days; this forecast period will extend to the next 10 days in the decades to come. Given that a perfect forecast (forecasting what actually occurs) would have a skill of 100%, typical weather forecasts now, for the first few days, have a skill of over 80%, decreasing as the time period lengthens and being less for precipitation than for temperature. Theoretical studies have shown that weather forecasts (forecasts of the correct sequence of events) are not possible beyond about two weeks. However, it is possible to predict the statistics of weather (e.g., more days of rain in the period of the forecasts, but without predictions as to which days), for the next month, season, year, etc. The statistics of weather is what we call climate.

Weather prediction is based on scientific analyses showing that the atmosphere, the oceans and other parts of the climate system are fundamentally "governed" by some "laws" of physics: Newton's laws of motion, conservation of energy and mass, and some relationships about the air or water that make up the atmosphere and the ocean. Weather and climate prediction models, based on these equations, are complex and non-linear and require huge amounts of computer time on very large computers to make their predictions. In non-linear systems, small differences can quickly become very large. Since our knowledge of the atmosphere will always be imperfect, these uncertainties can be amplified in the model and mask the real changes. That is why there is a limit of about two weeks on weather prediction. However, these models can still predict climate using these same principles and equations.

The atmosphere itself is a rapidly changing system. Its memory, whether there is the information in the atmosphere now that allows us to predict its state for the next week or month, is short. The ocean, however, has a long memory – years to centuries. The ocean also influences the atmosphere – the atmosphere is different over cold versus warm oceans. The ocean evolves slowly and we can use that slow evolution and its influence on atmosphere to predict the climate over the next season and longer. For example, the

El Nino phenomenon, a natural ocean-atmospheric 4-7 year period oscillation in the equatorial Pacific Ocean, influences global weather and climate through its tropical sea surface temperatures influencing the jet stream in mid-latitudes and the warmth or cold of a Canadian winter. The atmosphere-ocean system has several of these natural oscillations that can be used to make climate forecasts over much longer periods.

Key aspects of our solar system also fundamentally determine weather and climate. The Earth spins around its axis in 24 hours and orbits around the Sun in 1 year. These impose natural oscillations or cycles on weather and climate. Further, the shape of the Earth's orbit around the Sun and the tilt of the Earth's rotation axis vary on long time scales (20,000 to 400,000 years). These variations are the primary causes of the ice ages. Climate scientists use knowledge of these factors and the physical laws mentioned above to construct climate models (involving the atmosphere, ocean, ice sheets and biosphere). In computer experiments, a model of the oceans and atmosphere can be started with no winds or currents and at the same temperature everywhere. Then, the Sun is "turned on" and the Earth set spinning and rotating around the Sun. The model eventually simulates a climate that is very similar to our climate. It has seasons, rain and winds like our weather; it has ice ages that have their peak glaciation about every 100,000 years, as is the case for Earth. The ability of these models to simulate the past gives confidence that they can be used to project the future.

The atmosphere has a very short memory except for its chemical composition. Scientific analysis has shown that certain gases stay in the atmosphere for a long time. Water vapour is the single most important GHG, but human activities are only indirectly affecting it and, in addition, water vapour cycles through the atmosphere (evaporation to precipitation) in a week or two. As the climate warms, the amount of water vapour in the atmosphere will increase because warm air can hold more water vapour. This results in a positive feedback due to the increased greenhouse effect. Carbon dioxide, methane and nitrous oxide are the three most important greenhouse gases that human activities are now directly influencing, through use of fossil fuels, agricultural practises and other activities. Measurements and models show that the typical "lifetime" for a CO_2 molecule after being put into the atmosphere is about 100 years (ranging from 50-200 years depending on circumstances), for methane, about 12 years and for nitrous oxide about 114 years. Thus, these GHG influence the climate for long periods. Climate modellers have used the GHG concentrations for the past 100 years and then gradually increasing GHG concentrations to forecast possible climates of the future. Any projection of future climate change requires assumptions regarding the future emissions of greenhouse gases and aerosols which depend on assumptions of future economic and population growth, technological change, energy use, etc. In its Third Assessment Report, the IPCC put forth thirty-five scenarios of future emissions (called the SRES from the IPCC Special Report on Emission Scenarios) for a wide range of possible socioeconomic and technological futures. Using the combination of climate models and all emissions scenarios, the IPCC concluded that the range of projected 2100 temperature increase, relative to 1990, was between 1.4–5.8°C (Figure 1)[26]. Approximately one-half this range is attributable to the emission scenarios and the other half to variations between simulations of climate change by different models (for the same emission scenario). These models and their projections of future climate are discussed in detail in the IPCC report[27]. The Figure will be further discussed in the next section.

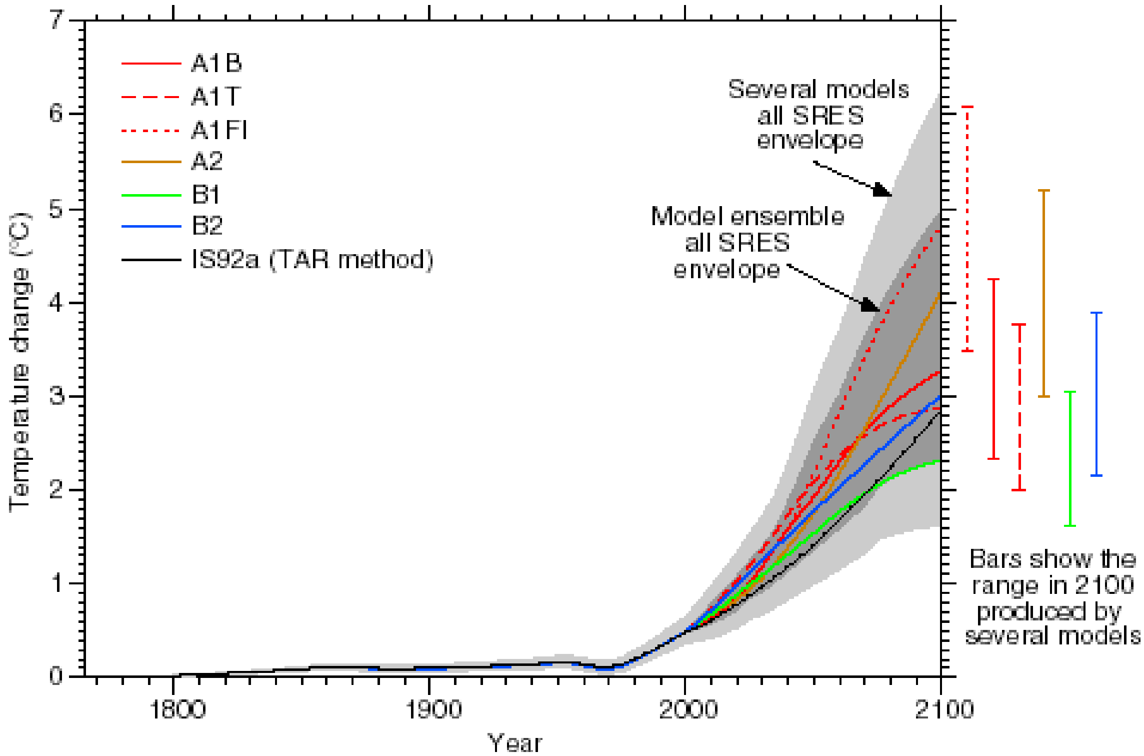

Figure 1. Graph of global mean temperature change (°C) plotted against time, for the period 1750 to 2000, as observed, and for 2000 to 2100 as projected by the IPCC (Third Assessment Report)[28]. The curves shown between 2000 and 2100 are averages of model results for six illustrative SRES indicated by the A1B to B2 (upper left) and an earlier scenario (IS92a). The darker shading represents the envelope of the full set of thirty-five SRES scenarios using the average of the model results. The lighter shading is the envelope based on all seven model projections. The bars show, for each of the six illustrative SRES scenarios, the range of model results in 2100.

In our every day life, we hear all kinds of predictions: economic, political and social, as well as weather. All predictions are done in a similar way: one observes and gathers information on the variables that define the present state of the economy or social conditions (or weather) and then uses a model to project the change in those variables into the future, the future states. The model is usually based on understanding past observations and is developed through making and analysing experimental predictions. To predict the growth in the economy, for example, over the next months to years, the model would need to include methods of estimating the personal and political decisions of many individuals, companies and governments, figuring out how they will interact and how the individuals will modify their decisions as they learn of the decisions of others. As yet there is no known set of “laws” that govern these decisions. In that sense, weather and climate models have a fundamental advantage, which shows up in the skill of their predictions. However, for climate change, the uncertainties of the socioeconomic models limit the overall accuracy of projections.

All in all, this understanding of the Earth's climate system and what causes it to vary and change, allow scientifically credible projections of change over the time scales of interest to the NWMO. The focus of this paper will be on change: how will the climate and weather be different from what it is now (now being the statistics over the past 30 years). However, it is important to remind the reader that there will always be uncertainties, the possibilities of surprises, so a risk management approach is absolutely necessary.

5. CHANGING VULNERABILITY TO WEATHER AND CLIMATE IN THE 21ST CENTURY

5.1 INTRODUCTION

In their consideration of future scenarios, the Global Business Network[29] identified, for the next 25 years, several issues including "*marked climate change*". Climate over the next century and beyond will change in many ways. It will be warmer, the growing season will be longer and the skiing season shorter. There may be more or less cloudiness. However, these changes are not likely to have any direct impact on the storage or transport of spent nuclear fuels. Clearly, above ground or near-surface storage facilities will be mostly impacted by changes in extreme weather events. As will be discussed below, there will be more high winds and/or more or heavier intense precipitation events causing damage or erosion to structures. There will be changes in total precipitation, lake and sea levels leading to different ground water conditions with impacts on underground storage. Changes in thermal characteristics of the ground could also influence underground storage [30]. Later in this review, consideration will be given to the possibility of glaciations.

Transportation of spent nuclear fuels may be by road, rail or ships[32]. In the NWMO Background paper on transportation systems, it is noted that road transport would now be restricted by inclement weather to 275-300 transportation days while rail transport is largely unaffected. With more extreme weather events, the number of restricted days may increase. All present reactor sites are located on a body of water so shipping is possible. With a warmer climate, there will be a longer ice-free season. However, lowering of the Great Lakes water levels would lead to shipping restrictions on the Welland Canal, St. Mary's River and the St. Lawrence Seaway and River. High winds may cause damage to structures, trucks, ships or trains. The key stimuli leading to vulnerabilities will be changes in extreme precipitation and drought, lake and sea level, winter cyclones, summer tornadoes and hurricanes. Extreme weather events can also lead to other natural hazards: such as, floods, storm surges, mud and snow slides, sea and lake ice motions and ocean waves.

Although the focus of Griffiths'[33] paper was security from terrorist actions, his definition of security "*to be a condition, never full realized, in which a referent entity or process is made and kept safe against harmful acts, events, and situations*" does apply to events like tornadoes and hurricanes. He also notes that "*the more spent nuclear fuel is moved* *about, year in and year out as it is produced, the more it is vulnerable to attack*." Again this would apply to extreme weather events and the transport of spent nuclear fuel.

The impacts of weather and weather-related natural hazards have been increasing around the globe[34]. In economic terms, the average annual costs have been doubling every 4-7 years to reach $US65B per year in the 1990s. These costs have been mostly due to weather-related extreme events. Although there are several possible factors (increasing populations, peoples' choices where to live, increasing wealth and, at the same time, widening disparity between rich and poor) on contributing to these increases, the conclusions of the Munich Reinsurance Company (one of the largest companies insuring insurance companies and very active in analyzing global information) and others is that climate change must be an important factor.

The IPCC has concluded that climate change is occurring, but the detection of change in occurrences of extreme events is much more difficult, since extreme events are by their nature less frequent. However, there is evidence for Canada of increasing precipitation and intensity of extreme precipitation[35]. The IPCC applied a set of criteria to assign values to probabilistic statements, such as very *likely* meaning 90-99% confidence that the result is true. Hence[36],

"New analyses show that in regions where total precipitation has increased, it is very likely that there have been more pronounced increases in heavy and extreme precipitation events. The converse is also true."

What will the next 100 years bring? As noted above, the IPCC concluded that the range of projected 2100 temperature change, relative to 1990, was between 1.4–5.8°C (Figure 1). In the next few decades, the uncertainty is less due to the impact of the GHG already in the atmosphere and because differences between models are still small; hence, increased confidence can be placed on the 20-y forecasts and these can be a basis for actions[38]. Climate change is inevitable and society will have to adapt to reduce vulnerability.

The IPCC further discussed the global mean temperature change in terms of reasons for concern. As the global mean temperature change increased from 1.4–5.8°C, the risks to unique and threatened natural ecosystems would increase from *risks to some* to *risks to many.* The distribution of impacts would change from *negative for some regions* to *negative for most regions*, while the aggregate impacts would change from *positive or negative market impacts; majority of people adversely affected* to *net negative in all metrics.* This analysis was done to demonstrate the increase in risks due to climate change as the global mean temperature change increased.

This paper will focus on extreme events on the assumption that these pose the greatest risk to structures and transportation systems. However, it is recognized that gradual changes will have impacts. For example, the gradual change in water levels or in ground temperatures or moisture content will change the environment in which spent nuclear fuel is stored or disposed. This could result in increased rates of leakage. Further, as the mean conditions change, the weather-related stressor may be closer to the threshold of impact with the result that a smaller extreme event may push it across that threshold. The IPCC noted that the risks from extreme climate events changes from *increase* to *large increase* as the global mean temperature change increases. To again quote Dr. Watson[39], Chair, IPCC: *"Indeed, during the last few years, many parts of the world have suffered major heat waves, floods, droughts, fires and extreme weather events leading to significant economic losses and loss of life. While individual events cannot be directly linked to human-induced climate change, the frequency and magnitude of these types of events are predicted to increase in a warmer world. "*

Climate change will lead to major changes in almost all aspects of the Earth's climate. This review will focus on certain elements that are felt to be most significant in terms of potential impacts and changes in vulnerabilities. In areas of present permafrost, which will experience thawing and hence providing an uncertain structure on or in which to build, construction of new storage facilities is not recommended. With the warmer temperatures will come changes in drought, ground water, lake levels and other characteristics of climate. These will have impacts on energy demand, on renewable energy supply, food production and population distributions, which is turn could have impacts on waste management facilities and transportation systems. These aspects will be discussed further in the following sections.

5.2 PRECIPITATION, DROUGHT AND GROUNDWATER

The IPCC projections suggest that all of Canada will see warming greater than the global average[40] with the Arctic regions to experience much greater than average warming (in excess of 40% above global average) in the winter. Projections for changes in precipitation are not as consistent. The IPCC analysis was in terms of amount of change and consistency amongst the nine models used in their analysis[41]. For southern Canada (south of 50^{o}N) and east of Lake Huron, the projection was for a small increase (between 5 and 20%) in the winter and inconsistent results in the summer. For Manitoba and the western half of Ontario, the results were inconsistent throughout the year. For Quebec and Ontario north of 50^{o}N and Nunavut, the models projected a small increase throughout the year. For southern Canada, with not much change in precipitation and increased evaporation resulting from warmer temperatures, there is expected to be a decrease in river runoff and groundwater. Precipitation amounts increase in the northern areas and over some of oceanic areas.

Model simulations have also been done for changes in extremes. Based on statistics over 21 year periods around 2050 and 2090, it was found that "*Extreme precipitation increases almost everywhere on the globe. Relative changes in extreme precipitation are larger than changes in total precipitation. On the global scale, the 20-yr return values of daily precipitation increase by 8% and 14% in 2040-60 and 2080-2100 respectively.*"[43]

The IPCC summarized their review of projected changes during the 21st century, as shown in Table 1[44]. Increasingly over the next 100 years, there will be increases in the probability of intense precipitation events (90-99% confidence) and droughts (66-90% confidence). The extremes of the probability distributions will become more important while the moderate conditions will be less prevalent. These conclusions apply to southern central Canada, but not likely to Atlantic Canada, due to marine influences. With the intense precipitation events would come the increased likelihood of flash floods eroding or damaging storage facilities. Intense precipitation events could also impact transportation of spent fuel, either directly on the transportation vehicle or on the road or railway that is being used. Use of weather forecasts and a precautionary approach could minimize these risks to transports.

Changes in Phenomenon	Confidence in projected changes (during the 21st century)
More intense precipitation events	Very Likely, over many areas
Increased summer continental drying and associated risk of drought	Likely, over most midlatitude continental interiors (lack of consistent projections in other areas)
Increase in tropical cyclone peak wind intensities	Likely, over some areas
Increase in tropical cyclone mean and peak precipitation intensities	Likely, over some areas

Table 1: Estimates of confidence in observed and projected changes in extreme weather and climate events. Virtually certain (>99% chance that a result is true); Very Likely (90-99% chance); Likely (66-90% chance); Medium Likelihood (33-66% chance); Unlikely (10-33% chance); Very Unlikely (1-10% chance); Exceptionally Unlikely (<1% chance).

Geological analyses[45] of sub-surface storage sites have shown that a desirable attribute of the geosphere for a deep disposal system is either stagnant or sluggish groundwater flow at repository depths. With the projected occurrences of droughts and intense precipitation events, the shallow groundwater around the Great Lakes, in southeast Manitoba and along the St. Lawrence would see a general decrease in the quantity and an increase in variability over time. The deeper the groundwater flow system, the more these variations would be dampened. The influences of changing groundwater on storage and disposal sites need further examination.

5.3 LAKE AND SEA LEVEL CHANGES

Lake levels are the result of a balance between net precipitation minus evaporation within the Great Lakes basin and out flows through rivers. Since the change in lake level results from a small difference among large numbers, the projections are quite model-dependent and estimates range from 0 to 1.5m lower for Lake Ontario and 0 to 3m lower for Lake Huron[46]. It is expected that all the Great Lakes will be lower and this will affect flows in the St. Lawrence. Since most of the spent nuclear fuel is stored along lakeshores, there are potential impacts on storage facilities through changing shoreline erosion and reduced influx of lake water into the ground water. Shipping piers would need to be lowered and ships using the canals and rivers would carry lesser loads and may not be able to pass through some areas. These impacts would gradually increase over the century.

Global mean sea level is projected to rise by 0.09 to 0.88 metres between 1990 and 2100[47], with the range dependent on the emission scenario and the model. Sea level rise is primarily due to thermal expansion and loss of mass from glaciers and ice caps. Confidence in model computations of regional distribution of sea level change is low but nearly all models project greater than average rise in the Arctic Ocean and less than average rise in the Southern Ocean. With respect to the Bay of Fundy, which has very large tides, rising sea level would increase the probability of impacts due to storm surges and lead to further coastal erosion and salt water intrusion into the coastal groundwater system. This would affect the geochemistry of rock formations around underground storage facilities if they were constructed near the coastline.

5.4 WINTER STORMS

Winter storms have great impacts in Canada, as is evidenced by the 1998 ice storm which almost closed the island of Montreal for weeks and cost the Canadian economy more than $5B. An examination of modeled changes in northern hemisphere mid-latitude low-pressure storms intensity found[48] that the number of storms decreased about 10% by the end of the century, but the number of severe storms increased about 40%. Since overall warming will make more of the winter season nearer the freezing point, the probability of ice storms would increase. Winter storms can impact structures through precipitation, with freezing rain having most direct impact and through the associated cold temperatures. The winds can damage structures and the combination of precipitation and cold can lead to freeze-thaw structural damage. Winter storms have an obvious impact on transportation systems and through their affects on communications, health services and other aspects of management that could impact the performance of a waste management facility.

5.5 SUMMER TORNADOES

Certain phenomena are not shown in Table 1, as they are too small to be represented in models, or there is a disagreement between models as to what might occur. The IPCC noted that, "*For some other extreme phenomena, many of which may have important impacts on the environment and society, there is currently insufficient information to assess recent trends, and confidence in models and understanding is inadequate to make firm projections. In particular, very small-scale phenomena such as thunderstorms, tornadoes, hail, and lightning are not simulated in global models.*"[49]

Thunderstorms, tornadoes, hail and lightning have impacts on structures and transportation systems. A single hailstorm in 1991 caused $360 M in damage in the Calgary area, mostly to automobiles.[50] Hailstorms are less intense in eastern Canada. Lightning and thunderstorms are prevalent across southern Canada. Tornadoes are particularly strong and devastating extreme weather events and they will be further discussed, in part as an example of risk assessment of extreme events.

Most Canadian tornadoes are classified as weak on the Fujita scale[51], which varies from F0 to F6. An F1 tornado is referred to as a moderate tornado with winds 117-180 km/h, resulting in cars being overturned, trees uprooted and carports destroyed. The majority of Canadian tornadoes over the past 20 years were in the F0 to F1 range. Only seven percent of the average 80 tornadoes per year across Canada during this period were F2, and about one percent, F3. An F3 tornado has winds 253-330 km/h resulting in houses torn apart, trains overturned and forests and farmland flattened. Statistics concerning tornado intensity may, however, be inaccurate due to the difficulty in measuring the damage done by tornadoes and almost 43% are officially unclassified. In the United States there are 800-1000 tornadoes per year and about 15% are of F2 intensity.

In the historical records of the Meteorological Service of Canada, only nine tornadoes have been classified as F4. No F5 tornado has ever been recorded in Canada, although there have been several reported in the United States, close to the Canadian border. An F5 tornado has winds 418-509 km/h and its impacts on houses is to level them or carry them great distances and cars are moved like missiles. An F5 tornado would be of major concern if it directly impacted on any aboveground structure or transportation system, no matter how robust.

An average F0 tornado track is about 40 metres wide and 1.7 kilometres long while an average F4 track is about 400 metres wide and 36 kilometres long[52]. Tornado impacts are often very localized so that the probability of hitting a given target is very low. Tornado warnings must be issued for a larger area because of uncertainty in predicting actual paths and the size of forecast regions. For example, Barrie, Ontario was impacted by a tornado in 1985. This was a multiple outbreak event that took 12 lives and caused about $200M in damages. The tornado watch area, as issued by the Meteorological Service of Canada, covered an area of about 10,000 km^2, while the area with significant damage was less than 100 km^2. So, even when in the watch area, the risk of being impacted was less than 1/100.

There are presently two major zones of tornadoes in Canada: across the western Prairies (mainly Alberta and Saskatchewan) and in southern Ontario. Tornadoes seldom occur in Atlantic Canada. Recent analysis[53] showed that lake breezes along Lakes Huron and Ontario influence the occurrence of tornadoes and hence the location of sites relative to the geography of the lakes matters. The authors noted that: *"there is a minor maximum (in tornado climatology) in southern Bruce County …"* near the Bruce reactor site. On the other hand *"On the north shore of Lake Ontario east of Toronto, only a handful of weak events have occurred to the south of the Oak Ridges moraine"* indicating less risk for the Pickering and Darlington sites. However, all are generally in a tornado-occurrence zone.

Projecting the changing risk due to tornadoes in a changing climate is difficult. There can be made, however, a circumstantial case for increased risk. Generally, Canadian tornadoes occur in the spring and summer when the daytime temperatures exceed 20^{o}C, and with warming there will be a longer tornado season. Climate models project increases in the number of hot days [54](defined as a day with maximum temperature greater than 30^{o}C) in southern Canada, by a factor of about 5-6, by the end of century. Further, as discussed in Section 5.2, there is expected to be an increase in the number of intense precipitation events, which often occur in the same kind of weather systems as tornadoes. Since tornadoes are known to depend on several factors beyond just the degree of "hotness" and intense precipitation, it is not justified to directly translate this information into a change in either tornado frequency or intensity. However, it can be noted that tornadoes occur in the area of the United States just south of Canada in much higher numbers per year. The percentage of F2 tornadoes is also twice as great (14% of F2, compared to 7% presently in Canada).

A fundamental issue is the management of risk in face of uncertainties regarding changing characteristics of tornadoes, in areas of Canada of concern to NWMO. Risk assessment is a topic of several papers in relation to the storage of spent nuclear fuel and also in long-term planning.[55] In developing a risk mitigation strategy, the question is: should strategies on spent nuclear fuel storage and transportation be based on the assumption of an increase in tornadoes? Most countries have adopted the precautionary principle and it can be argued on the basis of the precautionary principle that allowance for higher tornado risk should be factored into future plans. A parallel analysis invokes the rationale of Pascal's wager[56]. The question is: "will there be additional future risk due to tornadoes and should action be taken now to reduce the risk?" Action in this case would be to take additional precautions, probably resulting in additional investments in structures and care in scheduling transportation days. Pascal's wager poses the risk-decision in terms of consequences, depending on what actually happens, in the form of a decision matrix with four possible outcomes:

A. Tornadoes do increase in the future	B. Tornadoes do NOT increase in the future
A1. If we believe this and take action, we will avoid some of the serious impacts of tornadoes in the future.	B1. If we believe this and act accordingly (i.e., take no action), we will save ourselves any economic costs of additional investments.
A2. If we do not believe this and do not take action, we will have greater impacts from tornadoes in the future.	B2. If we do not believe this, and act accordingly (i.e., take action), we will waste the cost of the additional investments

Pascal's Wager suggests that only the downside risks be considered and ignore the upside ones. The downside risks, the bad things that may happen as a result of our choices, are represented by outcomes A2 (greater impacts) and B2 (wasted resources). It is probable that the magnitude of the costs of greater impacts (A2) far exceeds the cost of wasted investments (B2). This analysis needs to be done but it probably makes sense to avoid option A2. Hence, risk analysis indicates that we should take action on the basis of the prediction that the number of tornadoes will increase in the future. This action would be to make investments in reducing vulnerability, which is the same conclusion that arises from the precautionary principle.

5.6 HURRICANES

The IPCC (see Table 1) were also confident, at the 66-90% level that tropical cyclone peak wind intensities and mean and peak precipitation intensities will increase in some areas. More intense tropical cyclones, which are called hurricanes in the western Hemisphere, are of concern. 2004 is the 50th anniversary of Hurricane Hazel, an event that had great impacts on southern Ontario. Heavy rains, leading to flash floods, took many lives and caused great property damage. Hurricane Hazel resulted from the merging of a decaying hurricane (that had moved north along the US Atlantic coast and then veered northwestward) with a mid-latitude storm. Hurricanes generally have more impact and occur more often in Atlantic Canada. For example, Hurricane Juan had major impacts on Nova Scotia in November 2003. Hurricane Juan was a storm that was transitioning from a tropical hurricane into a mid-latitude storm. Research aircraft flights into the storm showed that the winds were much stronger than expected. As the storm moved northward towards Atlantic Canada, it attained a much greater forward speed of movement. To the east of the storm centre, the winds are the sum of the winds around the storm plus the motion of the storm and become very strong. Thus, the exact track of the storm will become critical in terms of winds and the impacts on structures. In the future, with the IPCC projection that there will be higher tropical cyclone peak wind intensities and with the sea level being up to a metre higher, there could be combinations of strong winds and storm surges impacting on structures in the coastal zone.

5.7 SUMMARY

Looking ahead to the remainder of this century, a changing climate will lead to higher risks of damage to above-ground storage (either at reactor sites or at a centralized storage site) and in any transportation mode due to increased probability of extreme precipitation and wind events (winter storms, tornadoes, hurricanes). For storage below ground, consideration needs to be given to the increased variability of groundwater with probably decreased volume in warmer soils. Reduced lake levels may also indirectly affect groundwater and will directly affect the efficiency of shipping on the Great Lakes. Sea level rise will impact the Point Lepreau storage site, exposing it to more threat from storm surges. Deep geological disposal would not seem to be very impacted in this time period. A concern, as climate change creates stresses on society, is that resources for the maintenance and governance of storage facilities will be diverted to address much more pressing, in the context of the times, issues

6. BEYOND THIS CENTURY - THE NEXT 100-300 YEARS AND THE POSSIBILITY OF SURPRISES

In looking to the period 2100 to 2300, the uncertainties in our projections become even larger. Hence, the approach must be the management of risks and recognition of the possibility of surprises. It will be assumed that nations will collectively modify their GHG emissions in order to meet the Convention's Objective of " *... stabilization of greenhouse gas concentrations in the atmosphere"*. In view of the present projected rates of increase of emissions for this century, it seems unlikely that stabilization will be achieved at less than 750 ppmv CO_2 equivalent (almost three times the pre-industrial value of 280 ppmv). Stabilization of atmospheric concentrations at that level (or almost any level below several times the pre-industrial value) will require reduction in global emissions to less than 50% of present values. Because of the long CO_2 life-time in the atmosphere, stabilization will only come in the 23rd century. After greenhouse gas concentrations have stabilized, global average surface temperatures would rise at a rate of only a few tenths of a degree per century, rather than several degrees per century as projected for the 21st century without stabilization (Figure 2)[57]. However, that would still be a further warming between 2100 and 2300 of about 1^{o}C in global mean temperature. It is possible that stabilization will be achieved at a lower level if nations take more action on reducing emissions. The lower the stabilization level, the smaller the total temperature changes.

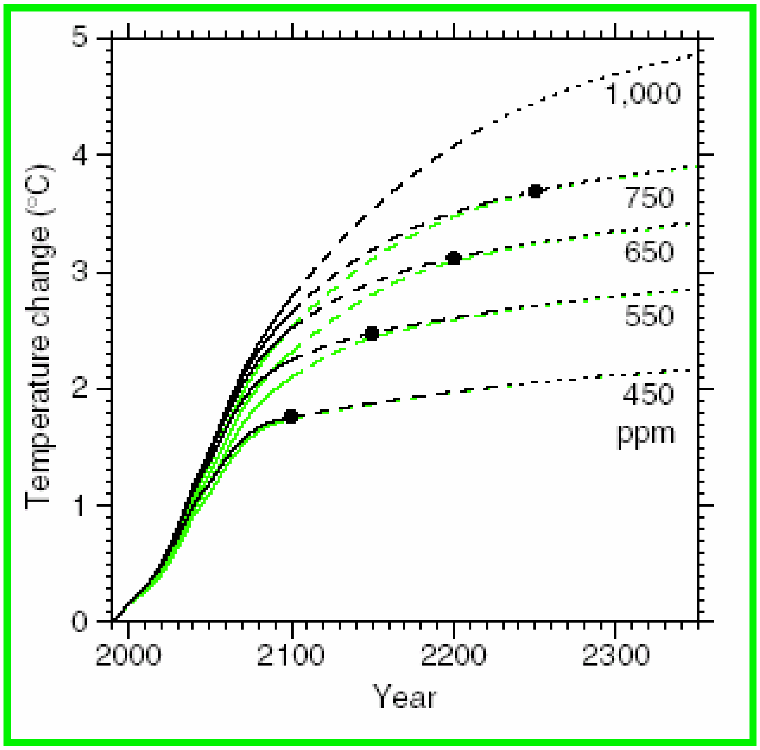

Figure 2: Climate model projected global mean temperature changes when the concentration of CO_2 is stabilized following IPCC emission profiles[58]. After 2100, the emissions of gases other than CO_2 are assumed to remain constant at their 2100 values. The projections are labeled according to the level of equivalent CO_2 stabilization. The black dots indicate the time of CO_2 stabilization.

From the point of view of extreme events, it is appropriate to refer again to Figure 1 and the discussion on increasing risks as the magnitude of the change of the global mean temperature increased. At 2100, as the global mean temperature increases from 2°C to 6°C, the risks from extreme climate events rises from "increase" to "large increase". Thus, as we look beyond 2100, we can use this information and the results in Figure 2 and Table 1 to conclude that there will be greater risk over the period 2100 to 2300 due to extreme weather related events.

According to the IPCC, the global mean surface temperature and sea level are both projected to continue to increase for hundreds of years after stabilization of greenhouse gas concentrations, due to the long timescales on which the deep ocean adjusts to climate change. Ice sheets will continue to contribute to sea level rise for thousands of years after climate has been stabilized. Continued warming could lead to further sea level rise, due to the melting of the Greenland ice sheet, of 1-6 m[59] over the next 1000 years. The West Antarctic ice sheet could contribute up to an additional 3 m to sea level rise over the next 1000 years. In the particular case of Antarctica, the prediction is very dependent on model assumptions, but these calculations highlight the risk of sea level rises of several metres beyond the rise of about 0.5 m (with a range of 0.2-0.9m) projected for 2100.

There is some risk of the full meltdown of the West Antarctic ice sheet that would result in a sea level rise of about 6m.

The Global Business Network[60] scenario analysis raises the possibility that greater dependence on fossil fuels through the coming century could result in *"rapid climate change ..., but not as predicted by the simplistic models of the early 00's".* They are referring to the possibility that non-linear processes in the climate system may be triggered as the climate warms well beyond the type of regimes that have existed over the past few thousand years. The models of the early 00's are not simplistic but it is entirely possible that they do not represent all processes. Much of the thinking about rapid climate change focuses on the global oceanic current (sometimes referred to as a conveyor belt), called the thermohaline circulation (THC), which transports large amounts of heat from the tropics to the North Atlantic region. Since this conveyor belt depends on the salinity and temperature of surface ocean waters in the high North Atlantic Ocean and global warming will freshen and warm this water, it has been postulated that the current may weaken and possibly stop. Analysis of ocean sediments and ice cores indicate that the THC stopped about 11,000 years ago when large amounts of fresh water flowed out through the St. Lawrence River as the last ice age sheets retreated and melted over North America. *"The possible shutdown of the THC would not result in a new glacial period, as press reports suggested; however, it clearly would involve massive changes in both the ocean and in the atmosphere. The most pronounced changes are expected in regions that are today most affected by the influence of the North Atlantic THC (e.g., Scandinavia and Greenland)." "The probability of this occurring is unknown but presumably much smaller than that of any of the more gradual scenarios included in the IPCC report. The probability is not, however, zero."*[61] "*The current projections using climate models do not exhibit a complete shut-down of the thermohaline circulation by 2100. Beyond 2100, the thermohaline circulation could completely, and possibly irreversibly, shut-down in either hemisphere if the change in radiative forcing is large enough and applied long enough."*[62]

As mentioned earlier, the atmosphere-ocean system has natural modes of variation, such as the El Nino – Southern Oscillation and the Arctic Oscillation. It is possible that anthropogenic climate change could change the characteristics of these oscillations. Changing the Arctic oscillation, by warming the mid-latitude oceans, so that it was more often in its positive mode would result in enhanced warming of the Arctic and could, hence, trigger major climatic changes. Another possibility is the positive feedback resulting from the release of methane gas, now frozen in the ground in the Arctic, leading to an amplified greenhouse effect. The risks from future large-scale discontinuities (abrupt changes) increase from very low levels, if global warming remains a few degrees, to higher levels as the amount of global warming increases. "*The possibility for rapid and irreversible changes in the climate system exists, but there is a large degree of uncertainty about the mechanisms involved and hence also about the likelihood or time-scales of such transitions."*[64]

In the period 2100 to 2300, the risks discussed for the 21st century (see Section 5) will increase, in magnitude and probability of occurrence. Storage sites and transportation systems will be increasingly vulnerable. Sea level rise will become a major issue as the ocean adjusts more slowly to the atmospheric warming of the past century. Hence, the

Point Lepreau storage will be at most risk. The increasing probability of droughts, interspersed with heavy precipitation events will affect the ground water regimes around shallow sub-surface storage sites. Any deeper disposal at further northern sites in permafrost areas will be very vulnerable as the warming penetrates further.

As we move through this period, there will be increased risk of unpredictable climatic changes as the global climate moves further from the regime of the past few thousand years.

7. LOOKING AHEAD 10,000 YEARS

To look beyond the time range of the IPCC, model projections must incorporate fully the influence of the Earth's orbital characteristics. A recent review by Berger and colleagues[65] has done this. The Earth's climate has very long time scale (100,000s of years) variations that will influence our future climate over the next 10,000 years. As the Earth rotates around the Sun, the orbit changes from being nearly circular to more elliptic; the dominant periodicity is 100,000 years, but there is also a slower variation over 400,000 years. Further, the tilt of the Earth's north pole varies on a time scale of about 40,000 years, from the present 23.5^{o} tilt to smaller values. There are other variations in the orbit and together these long period variations result in the Earth being closer or further from the Sun in the summer (and other seasons). When the Earth is further from the Sun in the summer or tilted more away from the Sun, the previous winter's snowfall may not fully melt by the end of the summer. If this continues, there will be a gradual build up of the snow and a glaciation occurs. The glaciation results in the positive feedback with the snow reflecting more of the Sun's radiation, further cooling the climate. And as the glacier builds it is higher in the atmosphere where it is cooler, resulting in another positive feedback. The glaciers build at the expense of water in the oceans, resulting in lowering of sea levels resulting in another positive feedback. Biological processes in the oceans reduce atmospheric greenhouse gases, causing a smaller natural greenhouse effect, further cooling the climate.

It has been observed through analysis of ice cores, ocean sediments and other indicators that "*nine times in the past 900,000 years, this region (much of Canada) has become heavily glaciated with the thickness of the dominant Laurentide ice-sheet reaching upwards of 4 km in its primary domes. In each 100,000-year cycle of glaciation and deglaciation the buildup to maximum ice cover has occurred relatively slowly over a timescale of 90,000 years whereas the retreat phase has been relatively rapid, lasting approximately 10,000 years.*"[66]

The 100,000-year cycle includes long periods where the Earth's climate is predominantly glacial followed by a shorter warm or interglacial period, with a minimum of ice. These interglacials, one of which we are now in, are typically 10–15,000 year long. Since we are now about 10,000 years into this interglacial, *"it is virtually certain that there will be major ice cover over Canada for a significant interval in the next 100,000 years."* [67] However, according to Berger and colleagues, the current interglacial will most probably last longer than the previous one for two reasons. Atmospheric greenhouse gas concentrations play an important role in long-term climatic variations. During the last two glacial-interglacial cycles, the CO_2 concentration was typically between 210 and 250 ppmv, except during the warm interglacial periods. Berger and colleagues experimented with different CO_2 values and found that no ice sheets developed if the CO_2 concentration was 290 ppmv or above. The IPCC scenarios, discussed in the last section, imply much higher values of CO_2 (between 450 to more than 1000 ppmv) by the end of the 21st century. These values will only slowly decrease (assuming a reduction of human use of fossil fuels). A second factor is the 400,000-year cycle mentioned above which means that the best analogue for the next 100,000 years is not the last glacial cycle but one that occurred about 400,000 years ago when the interglacial period lasted longer.

One of Berger's scenarios had a stabilized CO_2 concentration of 750 ppmv reached in 250 years, then decreasing to about 220 ppmv about 1000 years from now and continuing as such for 130,000 years. With elevated CO_2 values, the ice volume in the northern hemisphere decreases for 10,000 years and only returns to present values about 50,000 years in the future (Figure 3). Further, Berger and colleagues note that only after 50,000 years does the *"Eurasian ice sheet starts to grow significantly, followed by the Northern American ice sheet a few thousand years later"*.

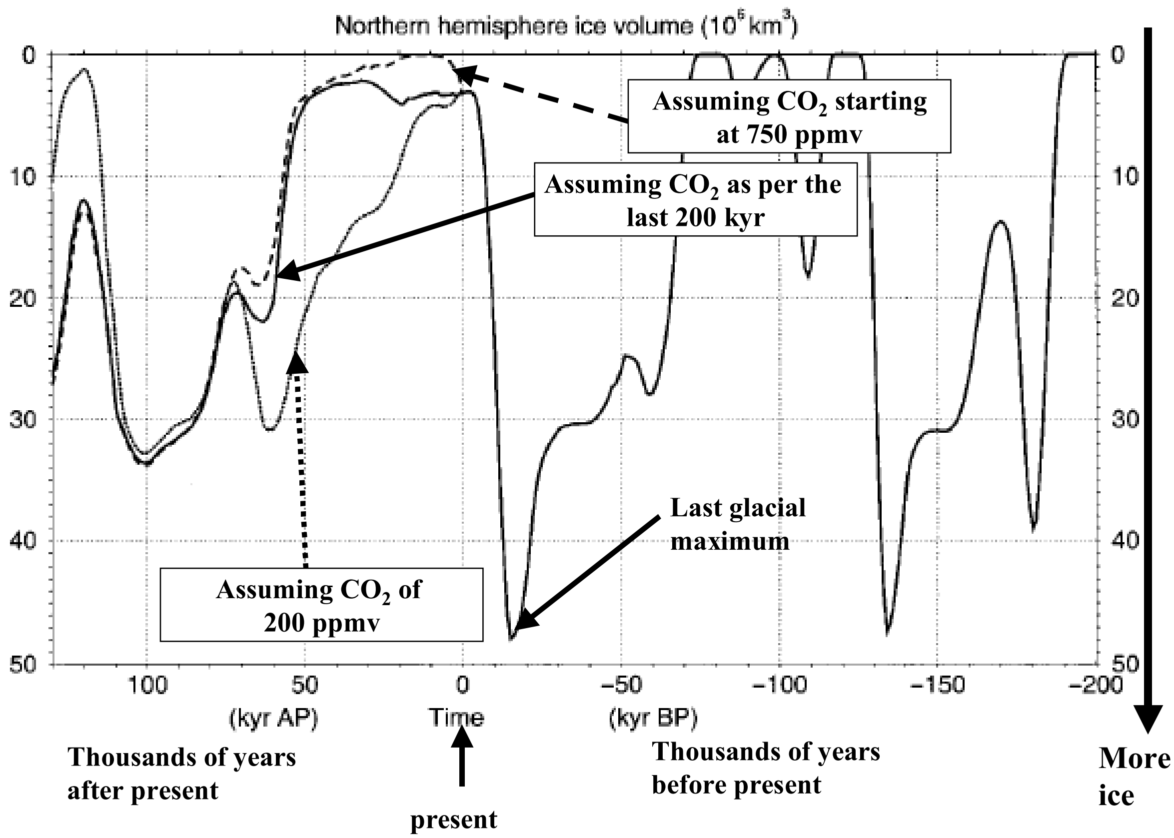

Figure 3. Simulated ice volume of the northern hemisphere Berger and colleagues' northern hemisphere climate model forced by solar radiation and atmospheric CO_2 concentrations. The simulation is shown for the period 200,000 years before present (200 kyr BP) to 130,000 years in the future (130 kyr, AP (after present)). The solid line is using the CO_2 values as observed over the last 200,000 years and

carried forward for the next 130,000 years. The dashed curve provides the results for the initially CO_2 =750 ppmv and then a decrease scenario. The ice volume increases downward. Time increases from right to left.

This research indicates that glaciations are unlikely to be an issue for the deep disposal of spent nuclear fuels over the next 10,000 years but will be an issue beyond 50,000 years. However, it is important that other research models also be used to simulate this case to increase confidence in this prediction.

It is unclear how human activities will influence the global climate beyond the next few hundred years. Models indicate that cumulative impact of the greenhouse gas emissions over the past and coming centuries will affect the climate for at least a few hundred years. The risks discussed in sections 5 and 6 will continue. If GHG concentrations gradually subside and no other (as yet foreseen) impacts take place, then the influence of the Earth's orbital variations will gradually dominate and the Earth's climate will move towards the next ice age. This will take several tens of thousands of years. The development of ice sheets over Canada would certainly have a dominating impact on nuclear storage sites. The impacts on surface storage and transportation modes would be overwhelming. The impacts on deep geological storage and/or disposal need careful examination. Of course, there will be great impacts on all of Canada and attention to nuclear disposal sites may be forgotten.

8. SUMMARY

This review has discussed climate and weather as basic characteristics of Canada and the globe. As the international scientific consensus developed that climate change was a concern emerged, the UN agencies created the Intergovernmental Panel on Climate Change (IPCC) as a body to undertake scientific assessments of what is known (and not known) about climate change science, its impacts and possible adaptation and mitigation strategies. The initial report of the IPCC led governments to agree to the UN Framework Convention on Climate Change and later its Kyoto Protocol as a means of working together to "*prevent dangerous anthropogenic interference with the climate system.*" It is now clear that climate is changing and will change at an accelerating rate in the coming century. Despite the international efforts through the UNFCCC, it is unlikely that atmospheric greenhouse gas concentrations will be stabilized within the next two hundred years. Stabilization of climate will only come after that while the full effects of sea level rise will take further hundreds of years to materialize.

The main arguments for concern about a changing climate rest on the validity of climate models. Although they clearly still have imperfections, they have been well enough validated such that the broad scientific community accepts their projections, with risk caveats.

Changing climate will bring with it more intense precipitation events, severe winter storms and stronger hurricanes. Lake levels will likely fall while the sea rises. Groundwater will be impacted through more frequent droughts interspersed with intense rain events. There is a risk of more tornadoes. These weather events will have impacts on all structures and transportation systems in Canada (and around the globe). The risks to above ground storage and transportation facilities for spent nuclear fuels will come from extreme wind and precipitation events. Near-surface, belowground storage will be at risk from changing thermal but mainly hydrologic characteristics of the ground. If shipping is used for transporting fuels, the lowering of the Great Lakes will impact on vessel capacity while sea level rise will impact the facilities at Point Lepreau. These risks will increase over the next few hundred years and risk and adaptive management strategies are needed. The IPCC scenarios provide a solid basis for the next 100 years and their projections for 2100-2300 were used as a basis for that period.

Over the next several hundred years, climate could stabilize but there is the risk of abrupt climatic changes or discontinuities. These surprises become more possible if emissions of greenhouse gases continue at high levels and push the climate system far from that of the past few thousand years. Model studies indicate that the onset of the next ice age will be delayed to past the next 10,000 years but it will inevitably come with major impacts on any surface facilities and risk to deep geological storage.

Climate change is a reality and it brings risks that must be factored into the long-term management of spent nuclear fuel. The scientific basis for the risk analysis is available and with an adaptive management approach, the new knowledge can be factored in as the decades pass.

The generic management options available to the NWMO are:

1. Storage, localized or centralized, with ongoing active monitoring, maintenance and governance, either above ground or below ground (either or both of shallow or deep)
2. Disposal, localized or centralized, with minimal need for monitoring, maintenance and governance, deep below ground.

Climate change will have implications for any of these options. As the physical climate changes, there will be increased risks, as discussed above, in above-ground and shallow below-ground storage, and for transportation, if a centralized storage or disposal approach is used. Deep disposal will have some risks due to long-term climatic change. Since ongoing monitoring, maintenance and governance will be needed, to different degree, in all options, the social changes induced by climate change will also result in increased risks.

9. LIST OF ACRONYMS AND DEFINITIONS

- **Anthropogenic** – caused by human activities, or human induced
- **Detection and attribution of human-induced climate change** – detection is the scientific analysis to determine whether there has (or has not) been change, while attribution is the scientific analysis to decide what is the cause of the change.
- **El Nino** - a natural ocean-atmospheric 4-7 year period cycle in the equatorial Pacific Ocean which influences global weather and climate. The main process is through warmer tropical sea surface temperatures, causing major cloud and rain systems, which then influence the jet stream and hence the warmth or cold of a Canadian winter.
- **Greenhouse effect and Greenhouse gases (GHG) -**
  - The **greenhouse effect** leads to warming the Earth's climate. Greenhouse gases (water vapour, carbon dioxide (CO_2), methane and nitrous oxide are the four most important) allow the Sun's radiation to pass through and warm the

Earth's surface but they retain the outgoing radiation from the Earth's surface. The result of the natural greenhouse effect has been to warm the Earth by about 33^{o}C compared to what it would be if there were no greenhouse effect. Human activities are now adding additional GHG (carbon dioxide and methane) to the atmosphere, causing further warming.

  - **Carbon dioxide** - CO_2 - measured in parts per million by volume. CO_2 is an important greenhouse gas.
  - **Carbon dioxide equivalent emissions** – since there are six greenhouse gases covered under the Kyoto Protocol and countries have the option of which to reduce in terms of emissions, scientists have created a system to equate the effects of reducing other gases to the effects of reducing carbon dioxide, the main GHG under the Protocol. These are called carbon dioxide equivalent emissions.
  - **Methane** - another important greenhouse gas
- **Ice ages (glaciations) and warm periods (interglacials or deglaciations)** – Ice ages have occurred naturally over the past million or so years. During an ice age, much of Canada was covered with an ice sheet, up to a few kilometers thick. Warm periods or interglacials are the periods when the ice sheets have retreated to only small areas (now Greenland, in the Northern Hemisphere). We are now in an interglacial period.
- **Intergovernmental Panel on Climate Change (IPCC)** – was created by the WMO and UNEP to provide scientific advice to governments on climate change science, impacts and adaptations and emission reduction strategies.
- **International Council for Science (formerly called the International Council of Scientific Unions – ICSU)** – an important non-governmental organization of scientists that plans and coordinates major scientific programs and represents the interests of scientists around the world.
- **Isotopic composition of the ice** – ice is frozen water and contains several chemical versions of water (different isotopes). The ratio of these isotopes depends on the temperature of the water when it evaporates and later snows to create Arctic and Antarctic ice. Once frozen in ice, the ratio remains as a measure of temperatures at the time the ice was frozen.
- **Kyoto Protocol**
  - A protocol under the UNFCCC
  - **Kyoto mechanisms** –
    - International Emissions Trading amongst developed countries;
    - Joint Implementation, which give credits for investing in developed countries;
    - Clean Development Mechanism which give credits for investing in developing countries; and
    - Carbon sinks, through management of forestry and agriculture, to help meet their targets
- **Memory –** a measure of whether there is the information in the atmosphere, ocean or other component of the climate system now that allows us to predict its state next week or month, years, etc.
- **Return values** – the average length of time between events. For example, if the data show that there were 5 floods in 10 years, the return period is 2 years. The term

arises from the sense of return on investment, in that planning and implementation of a flood control system should assume one every two years on average.

- **Sustainable development -** development that meets the needs of the people today without compromising the ability of future generations to meet their own needs.
- **Tornadoes** – intense rotating wind storms that occur in the summer, usually on hot days
  - **Fujita scale** – a scale from 0 (Light with winds 64-116 km/h and damage to chimneys, TV antennas, trees, windows and signs) to 5 (Incredible with winds 418-509 km/h and houses leveled or carried great distances, cars are like missiles) to 6 (winds 510-606 km/h and the area not recognizable) to rank tornadoes.
- **Thermohaline circulation (THC) or Global oceanic conveyor belt** - a global scale ocean current that arises due to sinking of ocean waters in the high North Atlantic Ocean, where the water is cold and salty (saline) (hence the term thermo (heat) and haline (saline)). Once the waters sink they proceed southward near the bottom of the Atlantic Ocean, then around Antarctica and gradually rise in the North Pacific Ocean. To feed the sinking process in the North Atlantic, warmer surface water moves northward associated in part with the Gulf Stream. This warmer water gives off its heat at higher latitudes, warming Europe, before it sinks. In order to maintain this circulation the surface waters must be salty enough and cold enough to sink. This does not happen in the North Pacific Ocean because the water is not salty enough (too fresh). If climate warming causes the water of the North Atlantic to become too warm or too fresh (by adding more rain or river inflow), then the THC will slow down and possibly stop.
- **United Nations Environment Programme (UNEP)** – a program of the UN
- **United Nations Framework Convention on Climate Change (UNFCCC) –** a convention to take action on climate change, agreed to by most countries
  - **Conferences of the Parties (CoP)** – meetings of the countries who have agreed to the UNFCCC, held annually
  - **Annex I Parties** - the European Union, economies in transitions (EIT)(countries of the Former Soviet Union and its allies) and others including Australia, Canada, Iceland, Japan, New Zealand, and United States – These countries agreed to undertake emission reduction targets in the first stages of the Convention.
  - **Annex II parties** (Annex I parties but excluding the EIT) - undertook financial commitments with respect to implementation of the Convention processes.
  - **Non-Annex I countries** – all who are not Annex I countries
  - **Commitment period** - the period 2008 – 2012 when countries are expected to meet their Kyoto targets
- **World Meteorological Organization (WMO)** – a specialized agency of the UN whose mandate is weather, climate, hydrology

10. KEY REFERENCES FOR FURTHER INFORMATION

The authoritative references for climate change are the reports of the Intergovernmental Panel on Climate Change (IPCC). These are:

- Climate Change 2001 - Synthesis Report. Contribution of Working Groups I, II and II to the Third Assessment Report of the IPCC, 395 pp
- Climate Change 2001 – The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the IPCC, 881 pp
- Climate Change 2001 – Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the IPCC, 1032 pp
- Climate Change 2001 – Mitigation. Contribution of Working Group III to the Third Assessment Report of the IPCC, 752 pp

All are published by Cambridge University Press (www.Cambridge.org) and are also available on the IPCC website (www.ipcc.ch)

A second very useful reference, giving a Canadian context to the climate change issue, is:

- Isuma, Canadian Journal of Policy Research, Volume 2, No. 4, Winter, 2001, a special issue on climate change with G. McBean as guest editor. (This is available in both French and English at www.isuma.net)

Other references are included in the endnotes below.

11. ENDNOTES – including additional references

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[13] The WMO) and UNEP established the Intergovernmental Panel on Climate Change (IPCC) in 1988. The IPCC has prepared three assessment reports: the first (First Assessment Report – FAR) in 1990; the second (SAR) in 1996; and the third (TAR) in 2001. The United Nations Framework Convention on Climate Change (UNFCCC) has recognized the IPCC as its scientific authority. For a review of background and processes of the IPCC, see Bruce, J.P., 2001: Intergovernmental Panel on Climate Change and the role of science in policy. Isuma, Canadian Journal of Public Policy Research, Winter volume, 11-15. Available at www.isuma.net. The IPCC website www.ipcc.ch provides background information and the Summaries for Policy Makers and Technical Summaries for the Third Assessment Report can be accessed there.

[14] Throughout this review, references to IPCC will be to Climate Change 2001 - Synthesis Report. Contribution of Working Groups I, II and II to the Third Assessment Report of the IPCC, 395 pp; hereafter referred to as the IPCC Synthesis Report. Through that report connections can be made to the more detailed reviews in the reports of IPCC Working Groups I, II and III. This particular point is referenced from IPCC Synthesis Report, pp. 5, 45-48, 180-185.

[15] IPCC Synthesis Report, pp. 5, 49-50, 171-175.

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[27] IPCC Synthesis Report, pp. 188-214.

[28] IPCC WG 1, Technical Summary, Figure 22

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