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ENVIRONMENTAL PREDICTION FOR CANADA:
APPLYING KNOWLEDGE TO PREDICT ENVIRONMENTAL RESPONSES

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ABSTRACT: This paper provides a brief overview of environmental prediction capabilities within Environment Canada. The purpose is to provide background and context that would be useful in considering future directions and priorities for environmental prediction initiatives within the department. A brief historical perspective of environmental prediction is followed by descriptions of existing and potential environmental prediction programs. The examples are chosen to illustrate important features of such systems and to set the stage for potential environmental prediction applications that Environment Canada would consider as prime candidates for future, or continued development. The paper closes with supporting information on the science and technology underpinning of environmental prediction within Environment Canada. This information provides a structure on which a cursory assessment of capabilities is based.

Keywords: environmental prediction, weather, Environment Canada

1. Introduction to Environmental Prediction

In the simplest sense, environmental prediction is the application of knowledge to predict environmental responses. In centuries past, this meant careful observation of repeating patterns in order to predict their recurrence. Over time, verbal predictions gave way to graphical associations and then mathematical calculations. The atmosphere and the stars were often the centre of attention. Until the 20th century and the advent of powerful digital computers, the amount of calculation required to apply mathematical methods to solve dynamic equations of atmospheric motion was prohibitive. Forecasts were based on observations at a single point.

Lewis Fry Richardson (1922) demonstrated a conceptual modelling framework, using people doing hand calculations that would come to fruition in the second half of the century with the advent of supercomputers and the birth of numerical weather prediction. Richardson's demonstration took six weeks to produce an eight hour forecast for one point, and it was out by a factor of 100. Today, scientists routinely produce accurate global forecasts of atmospheric parameters, days in advance, in about three hours, twice daily.

Environmental prediction extends far beyond weather forecasting, although most environmental prediction forecast systems today are coupled in one way or another to a numerical weather prediction model. The coupling can bring together economic, hydrologic, ocean, sea ice, air quality, forest fire, insect infestation and even disease propagation models with meteorological or climatological models to produce forecasts of new parameters of immediate value to Canadian decision makers and the public. Existing capabilities allow us to forecast flooding from storm surges, forest fire danger ratings, movement of ice edges in offshore drilling areas, energy utilization of ice breakers following different tracks through the ice, and wind energy potential for any location in the country. Potential applications are virtually unlimited.

The science of environmental prediction provides valuable input to decision support systems even when applied to past data. Detailed knowledge of environmental interactions, scenario modelling and sensitivity analyses can establish links between planned and unplanned, anthropogenic and natural events and the resulting environmental responses.

The ability to predict environmental responses resulting from a given set of initial conditions is at the heart of any environmental prediction system, no matter whether it is run as a hindcast, a diagnosis, or a forecast.

2. Examples of Environmental Prediction Success Stories in Canada

Modellers are never completely satisfied with their models. There will always be something that could be done a little more accurately or a little more efficiently. Still, the goal of environmental prediction model development in the public service is to migrate the models to an operational environment where the emphasis is on applying the models and delivering results to relevant decision makers in an appropriate timeframe. What follows are four examples of existing operational environmental prediction systems in Environment Canada.

2.1 Storm Surge Prediction

The Atlantic Environmental Prediction Research Initiative (AEPRI) gave birth to perhaps the best known example of operational environmental prediction systems in Environment Canada – the first operational storm surge prediction system in Canada (see Benoit *et al*, 2000). The storm surge model was born in 1999, out of the desire of a team of researchers in government, industry and academia to improve their environmental prediction capabilities. The model has since proven its value on numerous occasions.

The Atlantic Ocean off Canada's east coast averages one or two major storm surges each year – events in which atmospheric, astrophysical and oceanic conditions conspire to bring rises in sea level of up to two meters above the norm, in addition to surface waves. Storm surge itself is the result of the

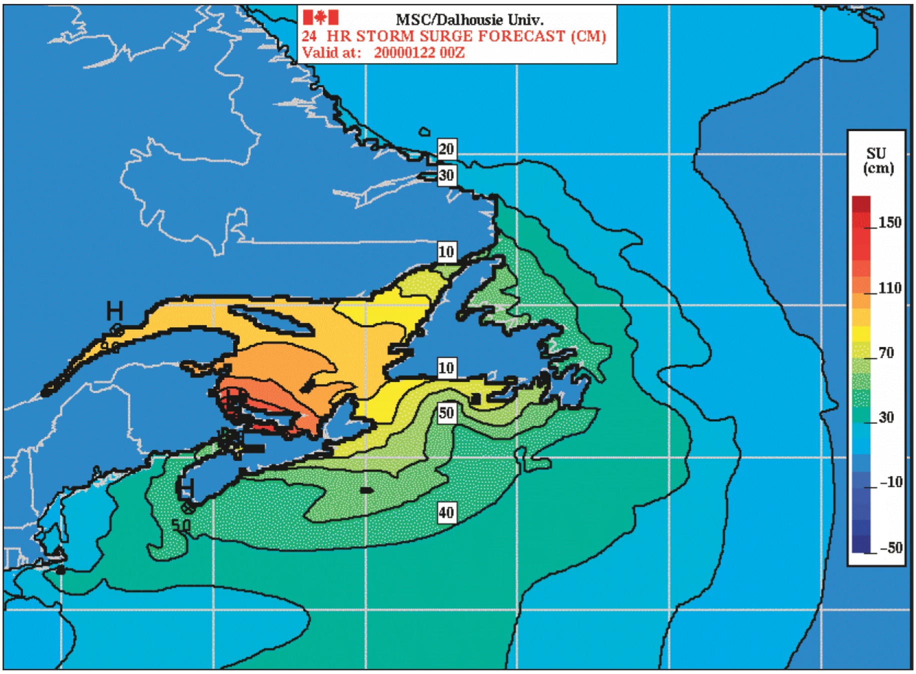

FIGURE 1

Extreme storm surge hit Charlottetown, Prince Edward Island, Canada on January 21, 2000. Source: Environment Canada.

interaction between atmospheric conditions, like low pressure areas and sustained winds, and oceanic conditions like the profile of ocean depth and sea swell. Together, these two effects can result in a rise of the sea level of half a metre or so. If storm surge occurs in concert with abnormally high tides, then it is possible for sea level to rise two meters or more above the norm – resulting in devastating floods. AEPRI made it a priority to couple an atmospheric and an oceanic model to ensure that the resulting environmental prediction system could be used operationally to warn the public of impending inundations.

Extreme weather, coupled with extreme tides can result in extreme storm surges and extreme consequences. The storm surge environmental prediction program aims to provide sufficient advance warning to alert Canadian decision makers and the public to the potential dangers that these combined events can present.

2.2 Ice Breaker Energy Consumption Prediction

The coupling of atmosphere-ocean models can support a wide range of environmental prediction applications and products. The additional coupling of a sea ice model can add significant value to shipping and resource industries working offshore in Canadian waters and in the busy shipping lanes of the Great Lakes and the St. Lawrence River. While most of these forecasts run in research mode, an increasing number of them are evolving into fully operational forecast systems.

Each day Environment Canada provides meteorological and related parameters to the Bedford Institute of Oceanography to support the routine production of forecasts of surface currents and sea ice to the oil and gas industry. The output from operational meteorological forecast models is used to drive, at six hour intervals, the coupled ice-ocean model, a surface wave model and a tide model. The forecasts extend out to 48 hours and make use of observed and modelled water temperature and salinity data, and digital maps of ice coverage provided by the Canadian Ice Service. The outputs are post-processed to produce forecast maps of surface currents, ice edge and sea surface elevation, as well as site-specific continuous graphs of significant wave heights. These products are critical to risk management associated with offshore shipping and oil and gas industries. The forecasts provide essential information for search and rescue operations and for the planning of oil spill response strategies.

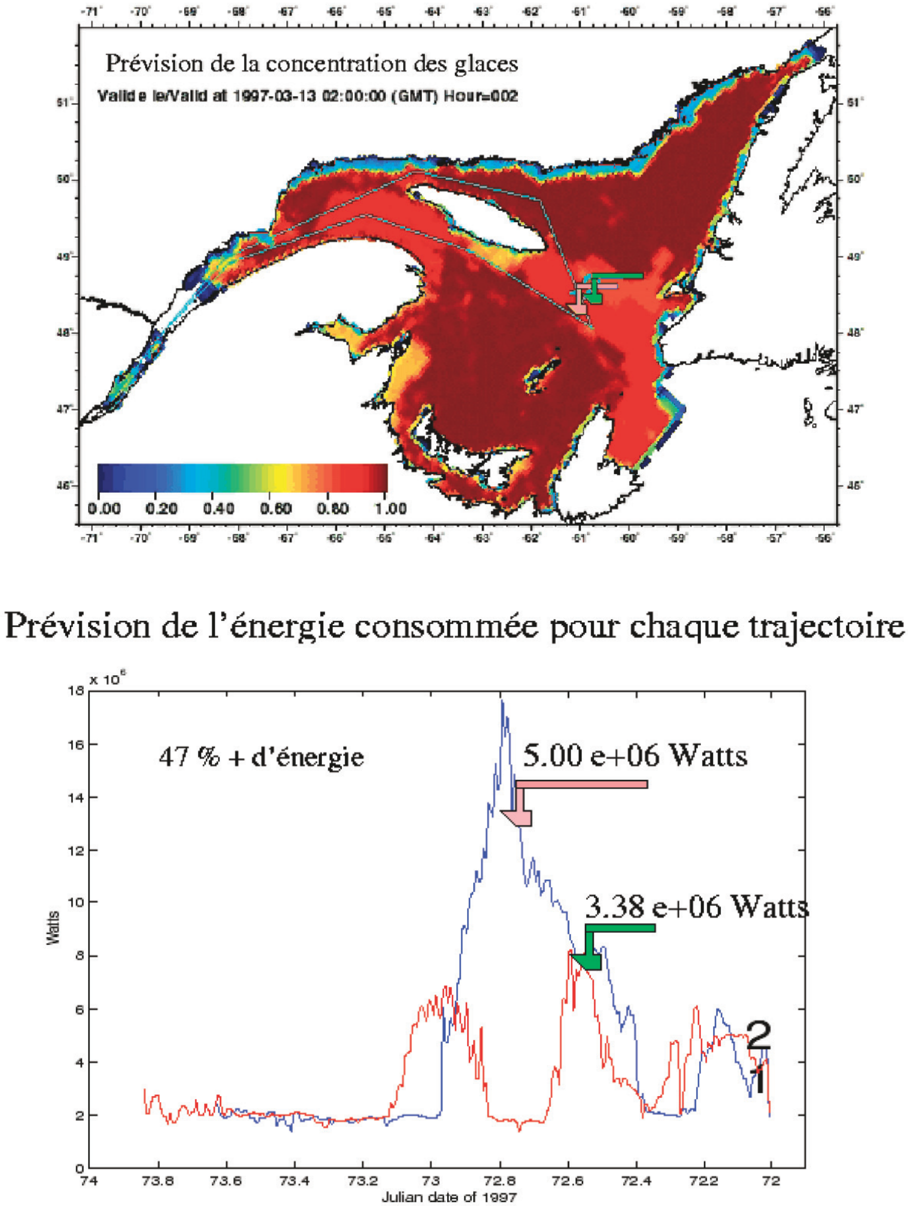

FIGURE 2

A 48 hour forecast that reduces energy consumption significantly. Source: Environment Canada.

Taking ice forecasts a step further to predict the time and energy required to move through the ice with ice breakers is the motivation for an environmental prediction system operating in the lower St. Lawrence river. A key element of sophisticated environmental prediction systems is making the leap from forecasting environmental variables to forecasting the significance of those conditions for specific applications. In this case, the parameters being forecast are not winds or waves or even ice thickness or coverage - they are energy consumption and time.

This expertise could prove extremely useful and valuable if shipping through Canada's Northwest Passage were to become commercially viable due to reduced ice coverage, as is predicted with future climate change.

2.3 Wind Energy Prediction

While it is perfectly natural to look to atmosphere-ocean coupling for environmental prediction, this system couples atmosphere-topography to model the effect of topography on wind speed and direction, and therefore

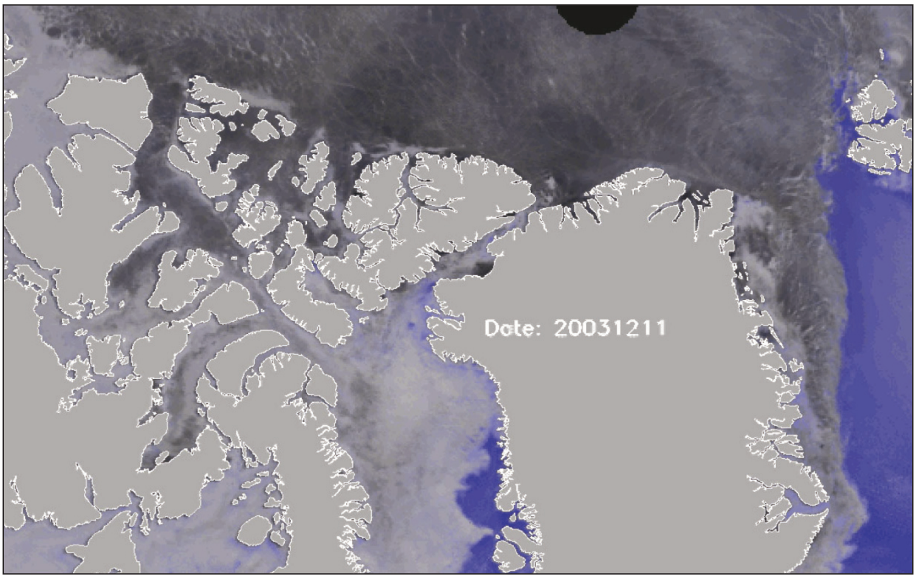

FIGURE 3

Ice movement in the Arctic Ocean and Northwest Passage. Source: Environment Canada.

wind energy potential. The predicted variable is not wind speed or direction but available wind energy. This parameter can be used directly in wind power generation models by large corporations, or even by individuals considering installing a wind power generator for residential use.

The use of wind power to generate electricity has come into widespread use in many parts of the world, and Canada is no exception. A decade ago, there were scattered wind power projects across the country, primarily in the province of Alberta, Canada and the Gulf of St. Lawrence, North America. Today, only two percent of Canada's power comes from wind energy but there is demand across the whole spectrum from individuals, to farmers and small businesses, to the large power generation utilities, to increase this proportion substantially. They are all after the same information – how much energy is in the wind at a specific location?

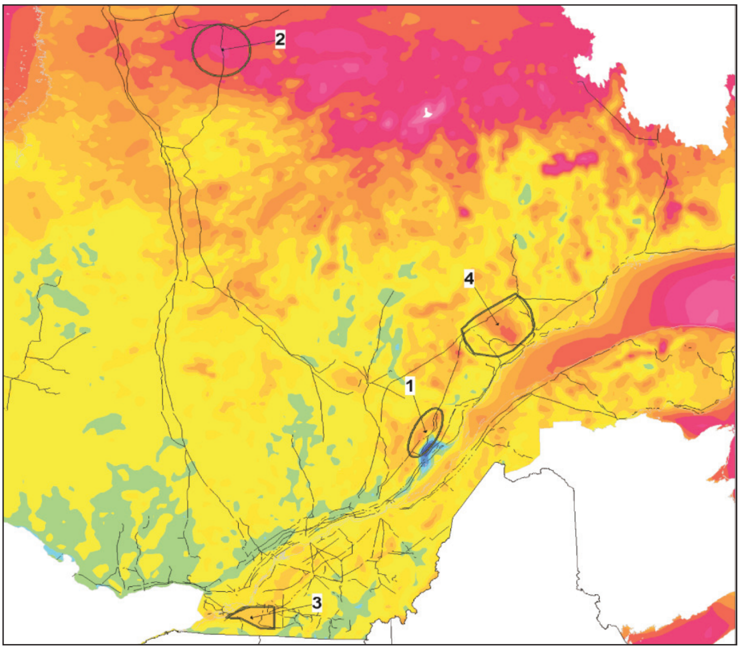

FIGURE 4

Mean wind speed over Québec. Source: Environment Canada.

In the past, this was a difficult question to answer. Most locations do not have a nearby climatological record of wind speeds representative of the location where a wind generator might be installed. Monitoring the wind for a couple of years would normally be necessary before wind power analysis could be performed to predict the amount of energy available. This is where Environment Canada's Wind Energy Simulation Toolkit (WEST) has proven its worth as an environmental prediction tool. The model can actually work backwards on historical archived data, or it can be used in predictive mode to forecast wind energy potential up to three days in advance. Both of these applications have significant value to end users.

WEST was used on climatological data to produce the Canadian Wind Energy Atlas. Statistical-dynamic downscaling was performed on long term data sets (43 years) and used to run a mesoscale meteorological model, MC2 (Benoit *et al*, 1997). This model effectively couples complex topography with meteorology, allowing analysis and prediction of wind fields over complex terrain, on a scale that is not achievable with the lower resolution operational weather forecast models. It uses orography and land class information on a 900 metre grid to calculate the influence of the topography and ground cover on the wind. It took a stunning 50,000 hours of CPU time on Environment Canada's supercomputer to calculate high resolution gridded wind fields, based on the coarser resolution original datasets. The results were post-processed statistically to produce mean wind speed and power at each model grid point. In fact, the output can be used to drive even finer mesh microscale models.

One result of all this work can be found at the web site www.windatlas.ca. Anyone can click on any particular location in Canada and find the wind energy potential and related information, along with simple tools that provide an instant measure of the power that any given turbine could generate at that location. In fact, the model has been used by a Canadian company to model wind power potential over the African continent. This serves to highlight an important point about environmental prediction systems. When they are designed well and produce outputs that are directly meaningful to end users, they can have economic value that far exceeds the initial investment.

2.4 Toronto Heat Health Alert System

The Toronto Heat Health Alert System illustrates how today's environmental prediction systems integrate information from a range of sources to produce forecasts of socio-economic variables. This system differs from the previous examples in that it is focused on a particular area - Toronto, Ontario, Canada. Like the other systems, it is driven by forecast meteorological variables, primarily temperature, dew point, cloud and wind, which are used to categorize weather conditions into one of eight synoptic classes. These same classifications were used to stratify mortality data for Toronto since 1981 and two of the weather classes, occurring on about seven percent of all summer days, were found to have a high probability of excess mortality (see Power *et al*, 2006; Dolney and Sheridan, 2006).

Twice daily in summer, weather forecast variables are fed into the model to calculate the likelihood of excess mortality. The heat alert system produces a forecast of likelihood of excess mortality associated with the forecast weather conditions. Model output is used by the Toronto Public Health system to

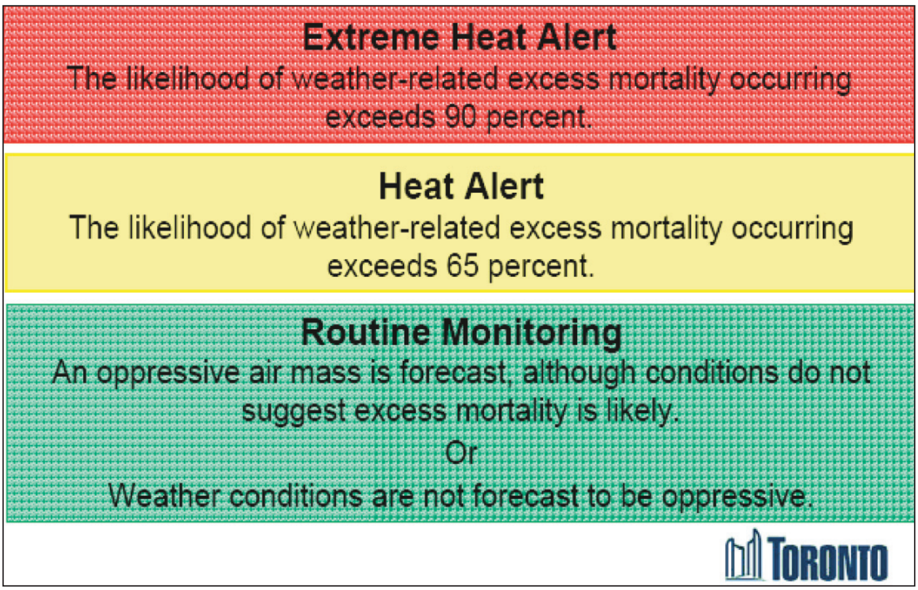

FIGURE 5

Heat Health Alert Categories in the City of Toronto, Canada.
Source: City of Toronto.

decide if a Heat Health Alert should be issued. The alerts also drive operational decisions on what measures should be implemented to help the public to cope with the conditions; decisions like contacting vulnerable populations, and ensuring bottled water is available at libraries, community centres and other air conditioned locations.

A distinguishing feature of environmental prediction systems, as opposed to weather or other forecast programs, is that they move beyond forecasting environmental variables to predicting the potential socio-economic impact of environmental conditions.

3. A Look Ahead for Environmental Prediction

The challenge for tomorrow's environmental prediction systems is to reach beyond environmental parameters to predict new parameters of social and economic significance.

Consider routine weather forecasts. Temperature, wind and humidity are forecast, but the combined effect of wind and temperature (wind chill) in winter, and temperature and humidity (humidex) in summer can have more meaning to the public in terms of the way they use the forecast – mainly to decide what to wear. Similarly, with environmental prediction the challenge will be to translate the significance of various states of the environment into terms that relate more directly to the sensitivities and needs of specific users.

The potential for environmental prediction programs to contribute exists in all sectors of Canadian life. What follows considers the possibilities using the broad headings of; the economy, the environment, health and safety, and domestic security.

3.1 The Economy

Canada's economy is inextricably linked to natural resources. The strength of the Canadian dollar in recent years has been highly correlated to strong pricing of oil and metals and is probably sustainable, based on the long reserve life of the oil sands. Resource development and production are highly sensitive to environmental conditions. Winter ice roads depend on extended extreme cold conditions; something which is becoming a problem in recent years as the warming of Canada's north continues at an unprecedented rate.

Spring and fall flooding shorten the winter season during which most of the drilling and tie-in of wells takes place.

Canada produces more hydro electric power than any other country in the world, meeting 62% of domestic demand. Lead times for construction of large hydroelectric projects can be of the order of decades. Clearly, this industry depends on reliable long range predictions of water availability in specific watersheds. Canada's forestry sector can suffer catastrophic losses from wild fires, windfall, glaze ice and major diseases and insect infestations, but forest yield modelling is not yet accurate enough to predict the likely impacts of these events.

These examples illustrate the point that moving beyond weather forecasts to couple permafrost or hydrologic models, forest yield and pest infestation models to numerical weather and climate prediction models could have significant value to the Canadian economy. Regardless of the balance between public and private sector delivery in these areas, the foundation will be laid with public sector environmental prediction science.

3.2 The Environment

The time and space scales of environmental issues can truly be daunting. From fast chemical reactions of natural and anthropogenic emissions to the almost geological timescale of climate change, there are issues affecting Canadians along the entire continuum. Effective management of these issues will undoubtedly depend on the best science and tools that environmental prediction systems can muster.

The quality, flow and availability of water within watersheds, the quality of the air, the diversity of ecosystems, the global carbon budget, the melting of sea ice are just a few of the issues of paramount importance to Canada's future. Comprehensive environmental prediction programs could bring together existing research projects and operational programs, across disciplines and government departments, to promote highly collaborative coupling of a wide range of numerical environmental models. Promoting a strong science base and ensemble (probabilistic) prediction approaches could spawn a new generation of environmental management tools supporting risk-based decision making processes – across all time and space scales. The challenge is to manage the science horizontally across disciplines so as to optimize the value gained from the resulting environmental prediction systems.

3.3 Human Health and Safety

Despite the heightened awareness that we all have about health risks from polluted air and water, and significant progress in many areas, we still see thousands of Canadians visiting hospitals each year with cardio-respiratory ailments following periods of poor air quality, especially when coincident with high temperatures and humidity. The prevalence of asthma, particularly in children, and its apparent connection to transportation emissions, and the health issues associated with ground water migration of toxic chemicals from contaminated sites, are some of the more pressing human health issues that could benefit from environmental prediction programs.

Existing operational programs like Toronto's Heat Health Alert are forerunners of more complex environmental prediction systems that could link epidemiological studies with air quality forecasts to generate appropriately structured products advising the public and transportation managers, as an example, of potential environmental health stresses. Here too, promoting a strong multidisciplinary science base is an essential prerequisite to developing a valuable environmental prediction system.

3.4 Domestic Security

Canada already has world class capability to predict the transport and dispersion of atmospheric pollutants on a global scale. Operational models are exercised whenever significant events take place. Such events have included the eruption of Mt. St. Helens (Chung *et al,* 1981), the Chernobyl nuclear incident (Pudykiewicz, 1988; 1989) and the terrorist attacks of September 11, 2001. Similar modelling capabilities exist for aquatic systems ranging from dispersion of e-coli in rivers to the spread of oil spills on the ocean.

Looking to the future, environmental prediction systems will be expected to model releases of a wide range of substances, ranging from biological to radioactive, in urban settings. This quantum leap down to the scale of urban canyons for such models is very demanding in terms of both the science and the technology required. Clearly, modelling the behaviour of these substances and coupling their evolution to a suitable urban meteorological model would be considered basic tools of any emergency response, but this capability will require significant development and validation before it could support a suitable tool for immediate responses.

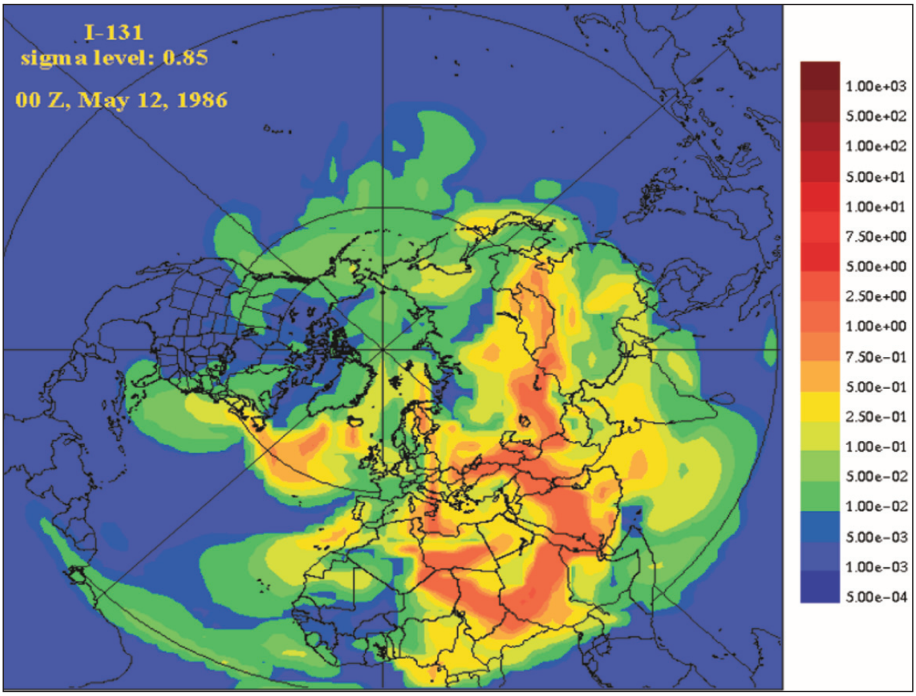

FIGURE 6

Modelling nuclear tracers with CANERM model. Source: Environment Canada.

4. The Foundation of Environmental Prediction – Science and Technology

Canadians expect their governments to manage a wide range of environmental risks related to human health and safety, domestic security, economic efficiency and ecosystem health. The challenge facing governments is to ensure a strong science underpinning to support informed and effective environmental policy and program development to maximize benefits to Canadians.

In the case of environmental prediction, technology also plays a pivotal role. Science and technology go together, hand-in-hand. Delivering operational environmental prediction programs depends on technology being available to collect appropriate data and feed it into the models, and on computing platforms and high speed data networks to actually run the models and disseminate results. Any consideration of future priorities for environmental prediction in Canada should take into account the essential nature of the science and technology foundation upon which such programs will be based.

4.1 Science

The science of environmental prediction is the science of representing the environment's behaviour through mathematical modelling of the processes and interactions that take place, on all time and space scales. Numerical modelling is the primary tool that is used to mimic environmental responses over a wide range of situations. These models can be used to perform historical analyses and hindcasts. Such applications provide new knowledge about how the models perform, since model outputs can be verified against actual outcomes, and they can also provide new insights into past events and the relative importance of various influences on environmental responses. Examples can include studies of the hydrological regime (or waterscape) of a region, based on historical data.

The models are also used in a diagnostic sense to improve representation of ecosystems and interactions in order to better understand complex processes influencing water quality, for example. In predictive or forecast mode, models are initialized with current data and instructed to step into the future to simulate conditions that have not yet occurred. In some ways this is the ultimate test of the science and the one that gains the most attention. Environmental prediction forecasts offer us new opportunities to make decisions and manage risks based on events that have yet to occur.

4.2 Numerical Modelling

In the science of environmental prediction intellectual capital is every bit as important as computing hardware. Canada made a strategic decision in 1962 to develop its own numerical weather prediction models to support operational weather forecast production. As a result, over the past four decades we have developed a pool of experts in numerical modelling that are recognized the world over for their excellence. This extends to the longer time frames of climate modelling as well. Environment Canada's weather and climate modelling teams have both been recognized in international peer reviews as being world class.

A quantum step forward came in the 1990s. Environment Canada scientists focused their efforts on developing a new dynamical core for numerical weather prediction – the very heart of weather forecast models on which all other processes depend. The Global Environmental Multiscale (GEM) modelling system (Côté *et al,* 1997) became operational in 1997 and has since exceeded expectations as an efficient and flexible framework on which weather, climate and environmental prediction systems can be built.

4.3 Coupled Modelling

Coupled modelling is at the very heart of any environmental prediction system. Coupling involves linking two or more numerical models so that they influence each other. For example, when atmospheric and oceanic models are coupled, there is interaction between atmospheric winds, pressure and other variables with oceanic currents, tides and waves, which in turn affect low level atmospheric winds. There are differing degrees of coupling, responding to differing computational loads, model complexity and feedback mechanisms. Coupled models may run online, so that the models influence each other at each time step, or they may be run semi-online or offline so that inputs from one model affect the other, but not at every time step. At an appropriate time interval, feedback occurs to maintain the coupling. The design of the coupling of numerical models is an important aspect of any environmental prediction system. The following quote from the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report illustrates the importance of feedback mechanisms between atmospheric chemistry, biosphere and climate models: "Failure to include such coupling is likely to lead to systematic errors and may substantially alter the projected increases in the major greenhouse gases" (IPCC, 2001).

CHRONOS (Canadian Hemispheric and Regional Ozone and NOx System) is an air chemistry mode. It is coupled with the operational numerical weather prediction model (GEM), an anthropogenic emissions model (SMOKE), and a biogenic emissions model (BEIS3/BELD3) to produce an experimental 48 hour forecast of ozone, fine particulate matter (PM2.5), and Air Quality Index (AQI) on a daily basis (see Pudykiewicz *et al.,* 2003).

There is more development to do before CHRONOS will be a completely operational modelling system. For example, aqueous phase chemistry and an

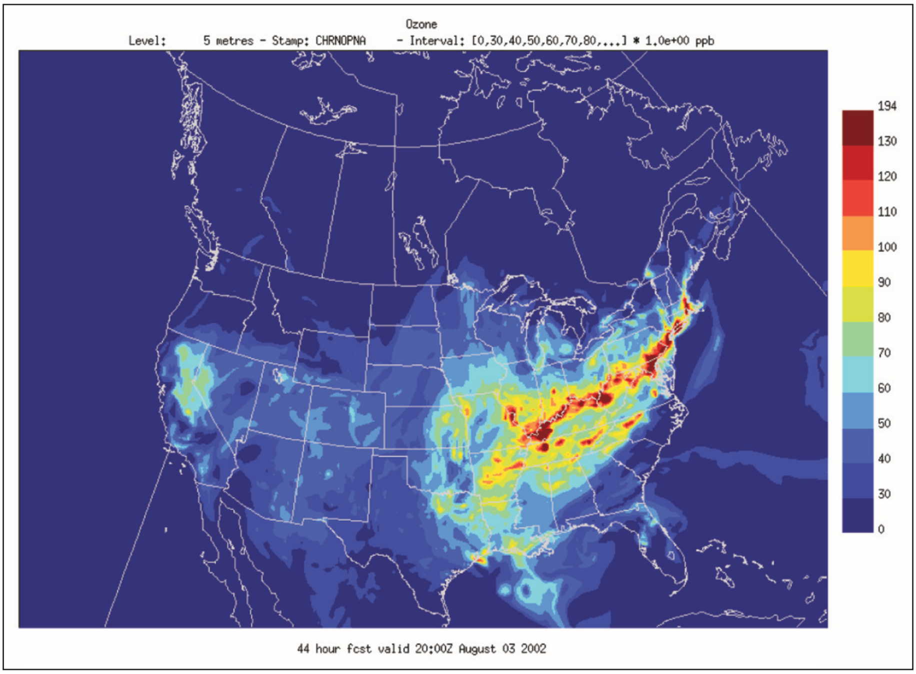

FIGURE 7

Sample CHRONOS (Canadian Hemispheric and Regional Ozone and NOx System) forecast of ground-level ozone. Source: Environment Canada.

improved data assimilation scheme are being developed, but the model already serves many useful purposes. It can be used in a diagnostic mode for scenario runs to see how emissions from different geographic areas are contributing to air pollution, in real time, and it is a major input to the daily forecast of AQI. This is something that will likely be common with environmental prediction systems of the future. Rather than forecasting specific environmental elements, in this case ozone and fine particulate matter, the outputs may well be indices, in this case AQI, or other indicators of the significance of environmental conditions to people, society or the economy.

A good example of this is a forecast of "loss of life expectancy" due to anthropogenic particulate matter less than two-point-five microns (PM2.5) levels (Amann, 2005). This is not a Canadian example, but it makes the point that environmental prediction is about much more that predicting significant environmental events; it is about predicting the human, societal and economic significance of those events. The RAINS (Regional Air Pollution Information Simulation) exercise used projected emissions and economic variables for Europe out to 2020 to compare how air quality might vary as a result of proposed emissions controls. They "froze" the weather to be the same as for the summer of 1997, in order to remove that influence. One innovative aspect of the exercise is that although individual pollutants were predicted, they were also combined into an integrated model that correlated loss of life expectancy to fine particulate matter (PM2.5) levels. The model's results predicted that throughout Europe there would be less loss in average statistical life expectancy due to identified anthropogenic PM2.5. We might see this as going one step beyond environmental prediction to environmental impact prediction.

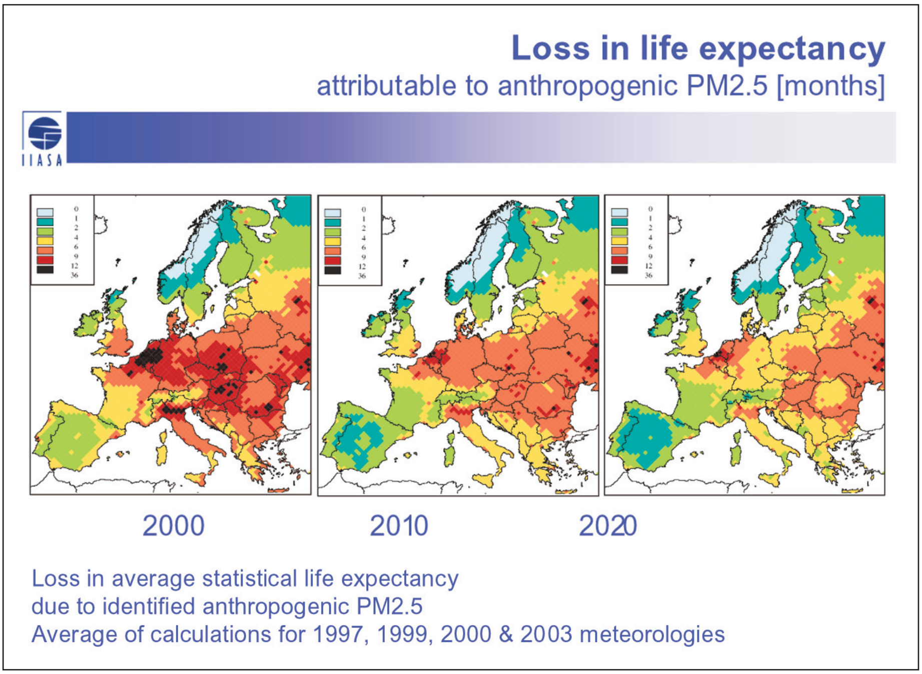

FIGURE 8

RAINS (Regional Air Pollution Information Simulation) projections.
Source : The International Institute for Applied Systems Analysis (IIASA).

Environment Canada has a reputation for world class global climate modelling (MSC, 2001) which involves long term coupled modelling of the atmosphere, land surface, oceans and sea ice. A recent development in this area uses Regional Climate Models (RCMs) to add a level of detail and value to climate scenario predictions that is not possible on a global scale (see Caya *et al*, 1995; Caya and Laprise, 1999).

Regional climate models are initialized by being nested within a global model and then running at approximately an order of magnitude finer resolution. For example, a limited area model (LAM) version of the GEM model could be employed to provide this resolution. The increased computational power necessary to run these models means that they cannot, at this time, be run on a global domain. By zooming in on a specific geographic area of concern, regional climate models provide downscaling of global climate model results. A Canadian regional climate modelling consortium (OURANOS) has been using a regional climate model, with ocean and sea ice coupling including coupling to a regional ocean circulation model (ROM). The model is being used to study a wide range of impacts of climate change on a regional scale. These include changes in the hydrology of major river basins in Canada – affecting hydro electric power generation, and the effects of climate change on land surface temperatures and snow depth with a level of detail that is not achievable in global models.

This downscaling of climate modelling, along with coupling to high resolution land cover, lake, ocean and ice models brings model outputs down to a time frame in which environmental predictions have immediate value to planning activities across a wide range of economic activities in Canada – particularly those in the energy and natural resources sectors.

4.4 Data

There cannot be an operational environmental prediction system without a corresponding operational data collection system. Historically, models were fed data collected from instruments at fixed locations and time intervals; each data point being somewhat independent of surrounding points. While this is still the modus operandi for many programs, and will be for many years to come, there are significant challenges associated with operating, maintaining and upgrading national networks of sensors, whether they are measuring water quantity or air quality. A related scientific challenge is to develop

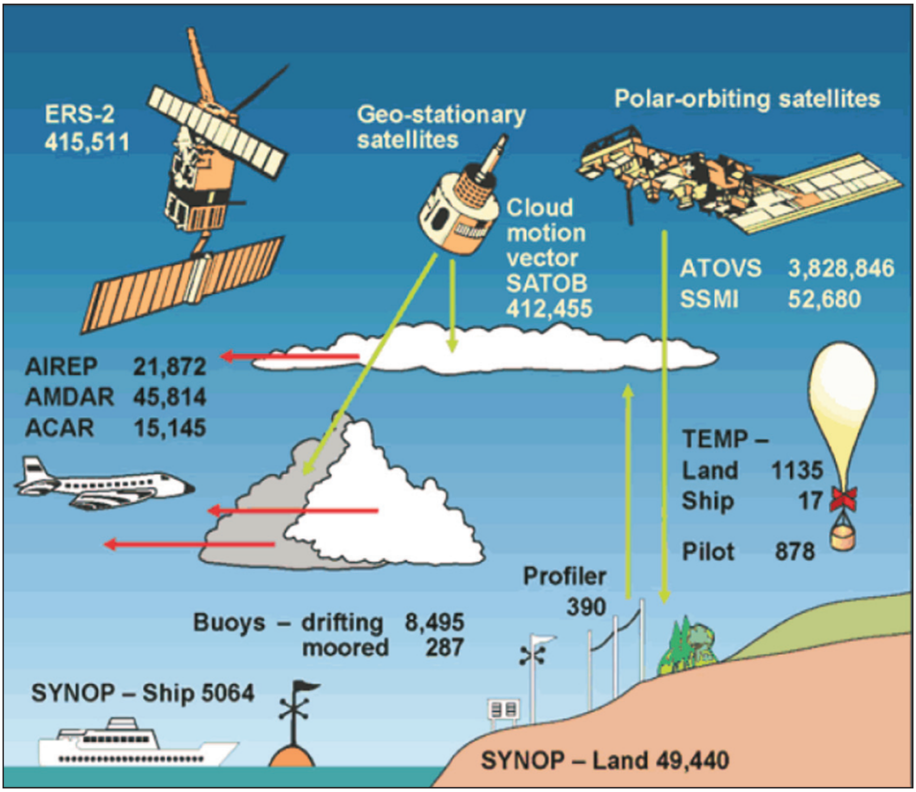

FIGURE 9

Typical operational data sources. Source: Environment Canada.

remote sensing techniques that are capable of increasing data density, in both space and time, while ensuring the precision and accuracy needed to initialize and update environmental prediction models. This is leading to a revolution in the field of data acquisition.

Today, satellites are becoming the preferred data collection platform and observations consist of a continuous stream of radiances, which are transformed algorithmically to represent a wide range of traditional and esoteric new fields. Ground-based systems are essential for validation and ground-truthing of space-based measurements. This shift away from fixed data points has created a whole new scientific challenge, that of assimilating the data into numerical models.

4.5 Data Ingest and Assimilation

With the proliferation of satellites as data collection platforms, new approaches need to be employed to assimilate data, as they are observed. These new systems, known as 4D-Var, or 4 dimensional variational assimilation, have been developed and implemented in operational weather forecast models. This approach paves the way for incorporating a wide range of environmental data, in real time, to environmental prediction systems.

Canada has demonstrated considerable expertise in developing and implementing satellite-based observing instruments, and even complete satellite systems that could support environmental prediction systems. SCISAT I was launched in 2003 to collect data for the Atmospheric Chemistry Experiment, studying atmospheric chemistry and dynamics affecting stratospheric ozone depletion. While the Canada-arm on the US space shuttles may be the most famous Canadian technology in space, Canada has developed numerous space-based observing instruments that, coupled with other Earth observing systems, could provide essential input to environmental prediction systems.

However, it is important to recognize the difference between research and operations. Research systems do not carry with them any obligation to replace failed sensors or platforms. If a particular system fails, it may not be replaced for years until a subsequent satellite is launched. Operational systems, on the other hand, have extensive backup and redundancy systems in place. If a satellite fails, a spare satellite is moved into position or a whole constellation reconfigured to ensure coverage. An operational environmental prediction system would require redundant data acquisition strategies that are not part of the existing research systems.

Canada is a member of the Group on Earth Observations (GEO). The overarching goal of the group is to implement a Global Earth Observation System of Systems (GEOSS). Such a system is intended to enable continuous and coordinated observation of the planet, at all scales. The plan is to build upon existing national, regional and international environmental observing systems to provide comprehensive coordinated Earth observations from thousands of instruments worldwide. GEOSS is expected to contribute significantly to environmental prediction programs, with socio-economic benefits in:

- weather forecasting;
- human health and well-being;
- natural and human based disasters;
- climate variability and change;
- energy resources;
- water resources;
- sustainable agriculture and desertification;
- terrestrial, coastal and marine ecosystems; and
- biodiversity.

In Canada, the value of GEOSS will likely also extend to forestry, transportation and Canada's northern regions.

The Earth Observation System (EOS) was established by NASA in 1991 and is evolving into an unparalleled suite of satellites and sensors, all intended to support mapping and modelling of the atmosphere, oceans and land surfaces of the planet. Canadian researchers and instruments are actively involved in EOS. The current stable of over 10 satellites is arranged in

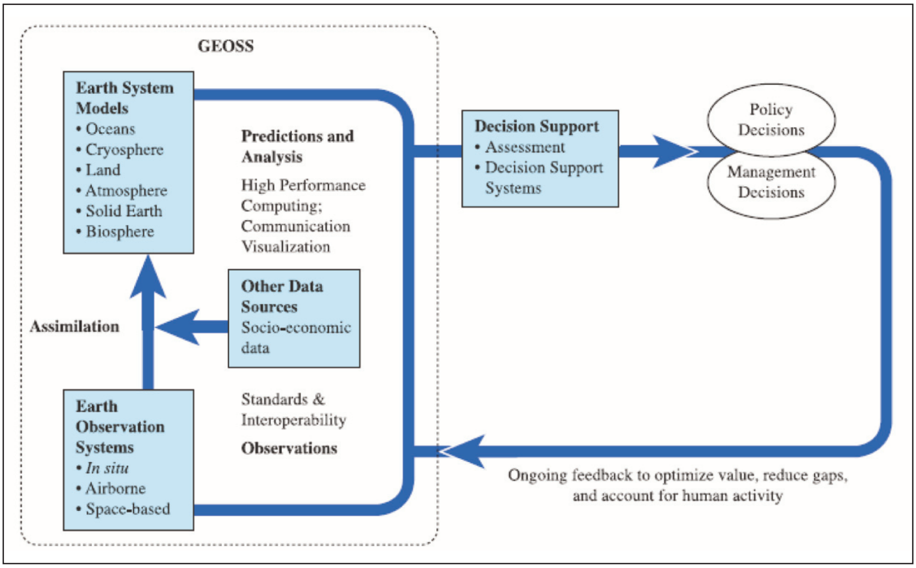

FIGURE 10

GEOSS (Global Earth Observing System of Systems). Source: US Environmental Protection Agency.

constellations and trains to methodically observe 24 physical variables over as much of the planet as possible on a daily basis. The results are high quality imagery and radiances of the atmosphere, sea ice, land surfaces, ocean colour, near-surface winds over oceans, rainfall and a whole host of sophisticated fields from specialized sensors, including tropospheric air pollution from the Canadian MOPITT instrument. Coupled with radar wind profilers and automated measurements from commercial aircraft, the potential data fields that could be utilized in developing environmental prediction systems has increased dramatically over the past decade.

Assimilation of high bandwidth, satellite and other data streams into operational numerical models has become a whole science unto itself. It depends critically on detailed information about systematic observational errors, which need to be incorporated into data assimilation schemes that become an integral part of model performance. Currently, the operational global GEM model runs use 4D-Var (four dimensional variational data assimilation systems; three space dimensions plus observation time as the fourth dimension).

Complex data assimilation structures like this are representative of state-of-science approaches to incorporating the exploding volume of semi-continuous data streams that will increasingly become the mainstay of environmental prediction systems. It is important to recognize that these assimilation schemes are model-dependent and it is most efficient, in terms of development expertise, to use a common atmospheric model and dynamic core for assimilation of the range of fields that could become operational in an environmental prediction system.

EP systems of the future will increasingly be driven by satellite-based, remote-sensed data supported by Earth-based ground-truthing and validation networks or observatories. Data of increasing complexity will be ingested in real-time and assimilated into sophisticated coupled environmental prediction modelling systems.

4.6 Technology

Operational environmental prediction programs depend on technology as much as they do science. The most sophisticated modelling frameworks are of little use unless computing platforms are available to allow them to be run at appropriate resolutions and time intervals.

While we might expect global capacities of computing facilities and data networks to continue to expand à la Moore's law, Canadian scientists will need access to world-class technology if they are to develop state-of-science environmental prediction systems. The highly transferable skills of scientists enable them to move relatively easily to organizations with leading technologies. It is in Canada's best interests to ensure that its scientists have access to world-class facilities in order to encourage continued research and development on issues of particular importance to Canada and Canadians.

4.7 High Performance Computing

It takes constant effort and investment to retain one's relative computing ability in the world. High performance computing is in an ongoing state of metamorphosis. The modern version of Moore's law states that computer speed doubles every 18 months. That suggests that a computer purchased today will be only half the speed of one purchased 18 months from now. A factor of two in processing power is a huge advantage in the world of environmental prediction. Infrastructure needs to be replaced constantly if we are to maximize the benefits to Canadians, which are highly leveraged to these investments. On the world scale of high performance computing Canada's weather forecasting supercomputer has ranked as high as 6th, in 1993 with its NEC SX-3/44. It now ranks 74th in the world with its new IBM cluster, although the new supercomputer is over 60 times as powerful (4.3 peak Tflops vs. 65 peak Gflops) as the previous one.

Over the past five years, over CAN$250 million has been invested in high performance computing infrastructure in Canada by federal and provincial governments, industry and academia. In 2006, high performance computing means grid-based computing, where high performance computing facilities are linked via high speed, high bandwidth networks. This infrastructure enables geographically separated data bases and models to be coupled and significantly increases the resources that can be applied to a complex prediction system – like environmental prediction.

Advanced high performance computing infrastructure is essential to carry out the kinds of simulations required for an effective environmental prediction system. It is also essential to retain the numerical modelling experts, who can apply their talents anywhere in the world.

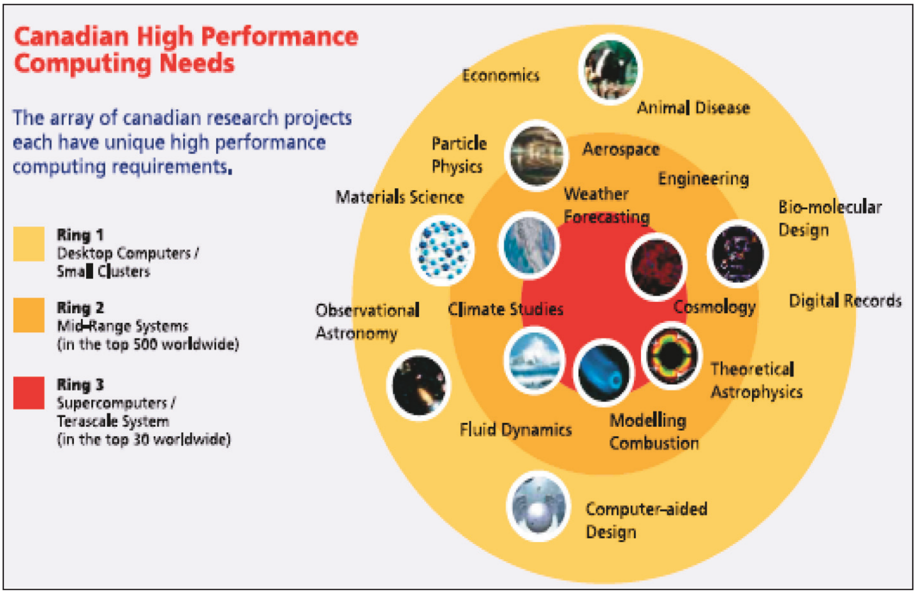

FIGURE 11

Canadian needs for high performance computing. Source: Rowe *et al.*, 2005.

4.8 High Speed Data Networks

With the rapid expansion of computing and modelling capabilities, there is a significant challenge to make the resulting outputs available to end users, whether they are the public or partners in developing environmental prediction products. This would not be possible without the high speed data networks that have really only become widely accessible in the past ten years or so.

The Internet has changed the way we work. Research that took endless hours of searching in public and private libraries and data bases can now be performed in moments online. The Internet pales in comparison to the speeds and bandwidth of data networks required for high performance computing, but advances are just as rapid.

Today's high performance computing systems are massively parallel systems employing thousands of processors all interacting through high speed interconnects. These systems can execute 40 Teraflops, or 40 trillion

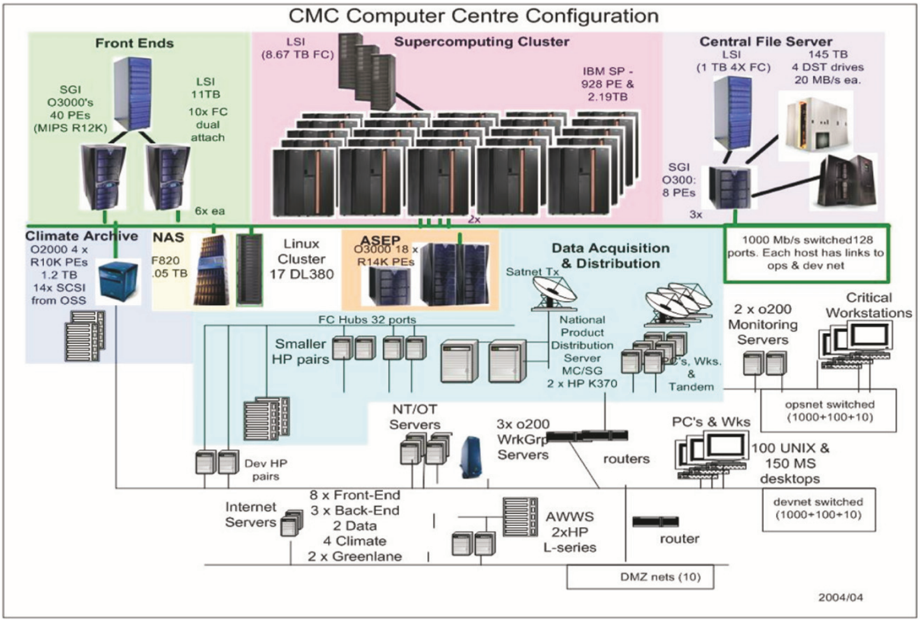

FIGURE 12

Schematic of the Canadian Meteorological Centre's data networks. Source: Environment Canada.

instructions per second. In addition to this, these systems now need to ingest observational data from dozens of satellites orbiting the Earth and transmitting data continuously, along with data from ground based systems like weather radars, ocean buoys and stream flow sensors. High performance computing systems can be likened to high speed rail transportation systems. Without the high speed tracks, in this case high speed data networks, they simply do not work. High speed data networks are essential, not only for data ingest but for the operation of distributed high performance computing sites, like those that could be used for environmental prediction.

Canada will not remain in the top tier globally without continued investment in computing facilities, expertise and data networks; any one of which could severely limit our ability to realize environmental prediction benefits for Canadians.

5. Conclusions: Can Canada's Science and Technology Meet the Environmental Prediction Challenge

This paper introduced environmental prediction, provided some Canadian examples of environmental prediction, and spoke of the future need for environmental prediction for the Canadian economy, environment, health and safety and domestic security. The core of the paper emphasizes the foundation of environmental prediction, that is, science and technology. But how solid is Environment Canada's science and technology foundation for environmental prediction programs?

In the science realm, specifically modelling expertise, Environment Canada has world class scientists and operational staff. They have been successful in coupling GEM, CGCM and MC2 to a range of ocean, ice, land and biosphere models. There exists a strong community of Canadian researchers pursuing regional climate modeling and other environmental prediction initiatives. In terms of coupled modelling, Environment Canada is well placed with respect to coupled modelling expertise and is part of a broader, active community within Canada. An environmental prediction initiative would accelerate additional developments, perhaps including atmosphere-biosphere coupling. For data assimilation, Environment Canada is world class in its data assimilation methods for operational weather forecast production. This expertise will be essential in accommodating the exploding suite of satellite data that will increasingly be available to support environmental prediction.

In the technological realm of high performance computing, Environment Canada was once in the very top tier of high performance computing, with the sixth most powerful computer in the world being used for operational weather forecasting. Its newest system ranks 74th and within a year will be below the top 100 in the world. The most demanding of environmental prediction systems will have to run on shared computing resources. As for high speed data networks, Environment Canada's data networks are adequate but capacity will need to be increased in the future. Sharing with other government departments and partnering with CAnet 4, a national optical Internet research and education network, could result in cost effective improvements.

While well-primed with a history steeped in environmental prediction, and a world-class level of expertise in the scientific and technological fields that support it, Environment Canada must seize the moment by ensuring that resources are available to continue to support the necessary foundation of environmental prediction that starts and ends with science and technology.

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