# *Forecasting in the 21st Century: Ninth IMO Lecture*

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# Forecasting
# in 21st Century

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## 1. Introduction

The Oxford Dictionary defines the noun "forecast" as: "conjectural estimate of something future, especially, of coming weather" and indicates that prediction is a word with very similar meaning. "Conjecture" is the "formation of opinion on incomplete grounds". The sense of estimate, future and incomplete information is certainly consistent with our sense of the work that we do. We usually think of forecasting as our process of looking ahead on the basis of knowing the present. In looking ahead, we recognize that we have incomplete understanding of how the "system" works and also that we have incomplete information on the present. In this paper, I am considering forecasting based on scientific understanding and methodology and how it is and will be applied to forecast the evolution of the atmosphere and its related components of the environment. In particular, the focus is forecasting in the $21^{st}$ century and how we can build upon the work done by national meteorological-hydrological services (NHMS). Being responsible for a major national meteorological-hydrological service that has undergone significant change over the past six years and developed extensive plans for the future, I bring a practical and personal point-of-view to the issues and will use the personal "we", referring to the collectivity of heads and members of similar services, or "I", in that context.

We are concerned with the atmosphere, that thin, life-sustaining envelope encircling the globe. Because the atmosphere knows no geographic boundaries, we must work together for our own, as well as our collective, good. The atmosphere plays a fundamental role in ecosystems and in the water cycle and is an effective connector of the world's ecosystems and, in recognition of this role, many of us are involved in environmental and ecosystem activities. Connected through precipitation and evaporation, the atmosphere and the world's water systems work in tandem. This connection is reflected, both at the international level, through the World Meteorological Organization, with its Hydrology and Water Resources Program and nationally where many meteorological services also serve as national hydrological services (and, hence, are NMHS).

The atmospheric and hydrologic systems are critical for all life forms while, at the same time, one life form, humans, is affecting them both. The atmosphere provides the oxygen that sustains life while providing a climate and a protective ozone shield against the Sun's incoming ultraviolet radiation that together make life possible. Water, in its liquid form, then provides the other essential element for life. Human activities are now creating pollutants that upon their release into the atmosphere, change its composition, reduce the protective ozone shield and change the greenhouse effect and, hence, climate. The atmosphere, in turn, transports and transforms the pollutants and eventually deposits them in places often very far from the point of emission. In this way, the atmosphere is a global mechanism, linking all countries and all people. Similarly, humans are modifying the water cycle, through damming or diversion of rivers, adding contaminants to both fresh water systems and the oceans, and in changing the surface and sub-surface characteristics of aquatic systems. We, thus, have natural systems with an increasing amount of human interference, such that human activities are for the first time having major influences on a global scale.

Our role, in the NMHS, has been to forecast the evolution of this atmosphere, the water systems and their linkages and influences on other components of our environment. With human activities now changing the fundamental nature of the atmosphere and aquatic systems, there is a need to include these environmental issues intrinsically into atmospheric and aquatic prediction models. The atmosphere has natural modes or scales of variability, both temporal and spatial, and including aquatic and other components increases the complexity of models and superimposes additional modes of variability. Pollutants emitted into the atmosphere and aquatic systems, have their own scales of variability which add to the complexity of predictions and through interactions can change the basic scales of variability.

Weather is the daily manifestation of the atmosphere. Weather can be holiday perfect, providing us with warmth and a pleasant ambiance for recreation and enjoyment. Weather can also be life-threatening and bring much hardship and even death to citizens around the globe. National weather and water services deal with forecasts and related warnings for hurricanes, tropical cyclones, winter storms, tornadoes, floods, droughts and other phenomena. The last years of the 20th century has left us with a legacy of extreme weather and weather-related events. Hurricanes, tornadoes, winter storms, floods and other such phenomena continued to reap havoc around the world. Unfortunately, there continues to be a tragic toll in human lives and the economic costs of weather-related natural disasters continue to rise. A new record for worldwide economic losses from such disasters was set in 1998, about $US 90 billion, almost a 50 percent increase over the previous record set in 1996 and about twice as large as the average annual toll during the first half of the this decade (Figure 1). In the decades 1960-89, the major world-wide cause of deaths in disasters had been civil strife, but drought and famine was the second leading cause of death, followed closely by weather (storms and floods). Fortunately, in countries where good weather warning systems are in place, the number of deaths has generally been declining. However, if we look at the number of people affected, then drought and famine plus weather (which were similar in magnitude) together accounted for about 90% of the global total.

Despite these ever-increasing costs to society, there is still need to build recognition by governments worldwide of the importance of considering weather factors in decision making. Weather is not a factor that can be ignored on the basis that “it happens; there is nothing we can do about it”. Although we have limited success in modifying weather on a day-to-day basis, improved forecast skill makes it possible to indeed do something about it. Confident weather forecasts are of great value in warning citizens of impending hazards and allow for many adaptive strategies to be invoked. Similarly, forecasts of an impending flood or a coming season of drought can be used to reduce loss of life and reduce socio-economic hardships. Generally, weather-related deaths and damage can be reduced by improved design and construction standards for buildings and critical systems; by relocating residences from hazardous areas; and by earlier, more accurate and more focused severe weather warnings. Analysis indicates that the latter approach, better warnings, is likely the most cost-effective and feasible approach. Governments need to be reminded that warnings and forecasts of hazardous weather and weather-related events can lead to significant reductions in the costs of hazards and the old adage “an ounce of prevention is worth a pound of cure” is certainly valid in this case. It is important that governments and international development agencies understand that investments in weather and water warning infrastructure and operations will result in significant return on investment, both in reducing loss of life and in reduced costs of remediation after disastrous events. Further, through understanding of the type of events that are possible, and their statistical probabilities, governments and citizens can plan their activities and modify their structures to minimize damages.

Interestingly, our improved ability to make confident forecasts of future states of the atmosphere or an aquatic system provides a new relationship with the future. Forecasts allow us to look ahead with confidence and these forecasts (or predictions) should be seen as a key part of economic development. This also increases our awareness of the impacts of societal activities that affect that future - both nationally and internationally. In some cases, forecasts of future states can lead to actions that change what actually happens; such as forecasts of urban air pollution or smog 2-4 days from now or climate change in the decades to come. We are now building in the possibility of deliberately reducing our forecast skill for these types of events. In a sense, fate can become a choice.

In pursuing enhanced human safety and security and economic growth, governments are recognizing that weather is an ever increasing factor in more effective governmental and individual decision making. As we enter the next century, changing climate will add to the pressures on us to provide further services and advice on atmospheric, hydrologic and related changes. These services will go far beyond the daily weather forecasts and include input to development of a wide variety of policies and plans, leading to protection of human health and to disaster mitigation and preparedness. In this context, decisions on investment, insurance, infrastructure, humanitarian assistance and a suite of non-traditional meteorological and hydrological "problems" will be at our doorsteps. In response, we will have to meet ever increasing demands for data, products and services, with issues of free and open exchange and easier access as continuing challenges.

Sustainable development has become the key focus of many national and international activities. Fundamental to sustainable development is knowledge of the future and knowledge of how different scenarios of the future will evolve, i.e., the impact or role of human activities in changing that future. Thus, prediction of the environmental-human interactions is fundamental to pursuing sustainable development. The NMHS of the world should be front and centre in considerations of and planning for sustainable development.

In this paper, the focus will be on the period 2010-2030, beyond the typical planning cycle but not so far away as to be uninteresting or uninformed, and with a slant towards policy issues.

## 2. Drivers of change

### 2.1 Socio-economic-political

The global population will continue to grow through to 2030, with increased urbanisation, resulting in up to 50% of the world's population being in urban areas. These megacities, though small in number, will have even greater influence on governments. Unfortunately, these megacities will often be located in coastal zones, adjacent to major rivers or in other areas of potential vulnerability due to weather or weather-related events; thus, the vulnerability of a large proportion of the population to extremes of weather and climatic conditions will increase. This will create a greater need for meteorological and hydrological services in terms of warnings and forecasts and in urban planning. Through more focused and improved services, pressing problems related to fresh water, food and energy supply, sanitation, transportation, protection against natural disasters, disease, pollution and health services management will become an ever increasing part of our mandate. With greater concentrations of people, it may be possible to enhance accessibility to weather services, provided that economic resources are compatible. In most countries, the NMHS is an organisation of the federal government. With the increased importance of megacities, and other levels of governments, such as provinces or states, it is appropriate for the weather and water services organisations to consider how, or whether they should, become multi-jurisdictional agencies, with responsibilities and support from several levels of government.

Governments will become more proactive in modifying behaviour to adapt to change, engaging educators and their institutions in resolving critical issues. Part of our role must be public outreach and education and we must bring along our citizens, partners and clients in use of weather and related information. They will be better able to use specialised information, but this effective interaction will only come with much effort by all parties.

Although the natural inclination is to assume that as societies become more developed and sophisticated, their susceptibility to weather would reduce, these is not generally the case. In the United States, it is estimated that about 40% of the economy is weather sensitive. The cost of weather-related delays to the air transportation industry is estimated to be $1B per year and improved forecasts could substantially reduce those and other airline costs. As "just-in-time" delivery for the manufacturing sector becomes more and more dominant, it is easy to see the negative influences of poor weather, and poor weather forecasts, on their economic efficiency.

Governments' role in providing services has been under challenge in many countries and an important consideration will be the governments' decisions on what services and activities they will fund and what they will not. In a general sense, governments should be protecting their citizens from factors beyond their control and providing a basis for molding the nation's future in the context of its past. We can define this as a general statement of what is "Public Good"; public good being what governments do. Further, since all citizens receive more-or-less equally both the services and benefits and it is not practical to exclude its benefits on a selective basis, it makes sense to have such services paid out of the tax base, rather than as a fee for service.

Warning citizens of impending dangers is a fundamental "public good" activity; for these reasons countries maintain military, police and fire services, and should include the weather warnings of hazardous events within the same context. It can also be argued that a role of government is preserving the basic heritage of the nation, the archive of its history - the national climate record. Beyond these basic public-good functions, there are arguments of national effectiveness and security and efficiency of scale that lead to an expanded role of the national weather service. For example, the infrastructure that makes a storm warning system possible also provides the capability to issue public weather forecasts, even when a warning is not warranted. None of this says that there must be a governmental organization that does these things, it could be a contract to a non-governmental organization, but it does establish the argument for government funding from general tax revenues.

Governments' public-good activities, in the context of the national weather service, should be to:

- protect citizens from impending dangers via warning mechanisms for hazardous weather events;
- maintain the archive or history of the nation; and
- facilitate mitigation and adaptation to weather extremes and climate variations.

In the context of environmental prediction that will be developed later in this paper, these statements should be modified to "weather, water and atmospheric-change related events".

Each government will make its own choices as to what is in its public good, but if NMHS agree on a common set of activities (or minimum list), it would likely lead to a greater degree of uniformity around the world. A different issue is how governments will chose to deliver these public good responsibilities to their citizens.

In most countries, the political principle of recognition (or visibility, identity or accreditation) for governmental services will be important and needs to be recognized by the private sector and between countries. It is unlikely that most governments will support the infrastructure necessary for observing and telecommunication systems if there is no visible recognition in the minds of citizens that the government is providing this service through their tax dollars. An additional issue will, for many countries, be ministerial or cabinet member accountability. A fundamental premise of parliamentary democracy is the accountability of the minister or cabinet member to parliament for the services or activities undertaken by his or her ministry. In many cases, this sense of accountability will influence the degree of control or independence that a weather and water service may have.

As we look to the future, it can be expected that there will be continuing needs and desires by governments and citizens for services, both in urban and rural areas. At the same time, there will be continued reluctance and/or inability of governments to fully pay for these services. Citizen demands for less taxation and more personal control will encourage governments to look at various 'free market enterprise' approaches to essential services. At present, governments around the world take a wide variety of approaches to economic and social issues and it is expected that that will continue. It will be a continuing challenge to maintain international cooperation and coordination amongst NMHS and related organizations, when some organizations are pushed to be fully cost-recovered and others are fully publicly-funded services.

Citizens around the world are becoming increasingly educated and informed. New modes of communications have given them a better appreciation of events happening around them. In the future, citizens will have growing expectations for:

- greater amounts of information;
- greater access to information;
- increased flexibility and timeliness of delivery of information; and
- higher levels of protection .

These expectations, which are of a general nature, will certainly be applied to weather and environmental issues. We can also expect that there will be significant criticism if these expectations for "information and protection" are not met. To develop their roles in this future, the NMHS must improve its outreach to citizens, using, for example, their public weather program. They must also increase their role in facilitating the development of a responsible social agenda that is aimed at solving, mitigating and/or adapting to the environmental challenges that lay ahead in the 21st century.

Management of risk, in a changing global scene, will continue to be a challenge, for weather services and for citizens and governments using their services. It is interesting, in this context, to think about risk management and risk communication, which are not the same thing. One of the important challenges for NMHS is to develop better our skills as a player in risk management and to understand better how to convey the sense of risk, i.e., risk communications. We also need to understand the relationship between warnings of risk, risk communication and society's response to risk.

If we give citizens a warning of a tornado in the next ten minutes, we expect that the response of citizens is to collect the children and run for cover. If, on the other hand, we inform citizens that there is an increased probability of tornadoes over the next season, we expect that their response will be different. There will be opportunities for coordinated actions by governments at all levels to prepare, including re-design of structures, building codes, etc., and better education and planning of response actions. Hence, the response to risk information depends also on the time scale of the prediction. The speed and effectiveness of citizens' response, in both cases, will depend on their understanding of the risk and how they should respond to it and to their confidence that the warning is something they should respond to. Both are based on past actions of the NMHS (record of public information and skill in forecasting).

Another example is the comparison of a smog forecast for today and that for smog later in the week. When the smog forecast is for today, the individual (as opposed to industrial) response may be limited to modifying their outside activities, adapting to reduce their exposure. If the forecast is for later in the week, individuals as well as industry can adapt their activities better to reduce emissions and, hence, reduce the smog level. On a much longer time scale, but similar in nature, we can think of and compare response strategies to a seasonal forecast of a warmer summer, climate variability, and a decadal to century forecast of warmer decades, i.e., climate change due to human-caused increases in the concentrations of greenhouse gases.

Risk communication is a difficult task because we, as scientists, communicate and think in different ways from the general public. For example, we will speak of probabilities, of averages, of acceptable risk and changing knowledge and the need for further research to reduce our uncertainty. The public is more likely to put risk in a very personal context, relating it to personal experience, a sense of "yes or no", not probability, and not wanting to hear that we need a further year (or decade) of study before giving an answer.

We, thus, have the scientific assessment of risk and the public perception of risk, which are probably different, unless we do a good job of risk communication, connecting the two. From the scientific side, we need to better translate our predictions, probabilities and risk assessment into understandable terms; we need to explain the uncertainties, knowledge gaps and research programs, in ways that can be understood; and we need to build credibility and trust. As we look at the public perception, we need to understand better how the public sees a risk, especially its qualitative dimensions; we need to acknowledge that they have specific questions; and we need to analyze the conditions needed to allow the public to acquire the required information, skills and participatory opportunities. Good risk communications has not generally been an area of concentration (or perhaps even interest) of NMHS in the past, but it is clear that we must address its challenges in the future.

The organizations, processes and discussions that were established to deal with the problems and arrangements of the 1950s to 1970s are having difficulty dealing the issues at the turn of the century; these difficulties will compounded themselves into the next few decades of the 21st century. A challenge will be effective relationships among WMO and NMHS to help deliver on the needs and expectations of the global community and its populations. An increasingly important factor will be the role of national and transnational private sector organizations which add to the complexity of our relationships. Our challenge will be to maintain international cooperation and coordination in a changing landscape and to find adaptive responses and flexibilities. For both the NMHS and WMO, there is a need for better cooperation and coordination with non-governmental sectors, both service providers and media organizations and this challenge needs to be met now..

In some sense, it is harder to predict the evolution of the economic, social and political forces which will influence us, than it is to predict climate change. Hence, we must develop adaptive responses and flexibilities that will serve us through a variety of changes.

## 2.2 Science

Science will continue to be a major driver of change. Scientific advances in understanding and predicting the coupled atmosphere-land-water system have led to major improvements in forecasting over the past decades as can be see, for example, in Figure 2. Through advances in science, technology (including computers) and observing systems, there has been a continual increase in the skill in numerical weather predictions of 500 mb patterns (and other characteristics). The skill of a 3 day forecast in 1997 is a good as that for a 1.5 day forecast in 1978. Some of this increase in skill can be attributed to the Global Atmospheric Research Programme (GARP) which was conducted under the joint sponsorship of the WMO and the International Council of Scientific Unions (ICSU) between 1967 and 1980. The first objective of GARP was to reduce the errors in forecasts for day 1 and beyond. It did not focus on the short-term forecasts of hours up to a day.

We can expect these improvements in skill to continue in the future. By 2010, both the World Weather Research Programme and the Climate Variability and Predictability Programme (CLIVAR) of the World Climate Research Programme will have completed more than a decade of research. Based on the success of these projects' predecessors, we can be confident that significant advances will be made. Recent developments in numerical weather prediction show that models with spatial resolution as small as 1 km and extending over long time periods and large spatial domains will be functional by 2010. These will become more effective and less costly in a relative sense, by the continuing advances in computational technology. Other areas of advance will be in the development and implementation of new observing systems and the assimilation of this information in weather prediction models. For example, the inference of atmospheric structure from GPS information shows great promise. Whereas we used to use only standard meteorological data (winds, temperatures, pressures) at fixed points and times in numerical weather prediction models, four-dimensional data assimilation systems allow the use of data from varying points and times, and equally importantly, the assimilation of other quantities such as measured radiances from satellites or the refractive index information from a GPS system. Further, with satellites such as the Tropical Rainfall Measuring Mission (TRMM), direct information on precipitation can be ingested.

In the future as the present, our key activity will continue to be warnings of extreme events, such as, tornadoes, winter storms, typhoons, air pollution episodes, seasonal climatic variability, and long-term climate change, which are our fundamental mandate for protection of life and property and the basis of our work. On a day-to-day basis, the most fundamental will be warnings of severe weather. We will continue to follow the sequence of advisory, then watch and finally, the actual warning. However, we will have extended the time frame so that our initial advisory may be 7-10 days ahead, with the watch also initiated much earlier. These advanced skills in giving warnings will allow for much more effective response to them. As our lead times and accuracy increase and our false-alarm ratio diminishes, we will see public confidence and response greatly increase. Warnings result from a synergy of predictions of the future through numerical models and better observations through satellites and other tools, placed in the hands of skilled meteorologists. One of the tools for improved severe weather forecasting will be Doppler weather radar and lightning detection networks. Doppler weather radars have been in use for some years but there is still great potential for enhancing their use for severe weather warnings. With appropriate funding, we expect that there will be greater use around the globe. Doppler weather radars can be used more effectively through improved algorithms that are better able to detect severe weather events earlier and more reliably. One example is detection of mesocyclones that lead to tornadoes (Figure 3).

Information from Doppler weather radars can also provide valuable input into forecast models. As data assimilation systems are being upgraded and enhanced, it is essential to plan on using all possible types of data. Wind profile information from Doppler radars will form a main input to weather prediction models of the future (Figure 4). Well-calibrated weather radars will continue to be an important tool for monitoring areal precipitation amounts and input to quantitative precipitation forecasting.

As better atmospheric model capability is developed, this must be coupled with other components of our physical environmental system. One of the most important of these is the hydrological cycle, leading to better forecasts of floods and droughts. An example of coupling a high-resolution atmospheric model with a hydrological model for enhanced flood prediction is the case of the Brig, Switzerland, flood of 1993. The Brig flood resulted from a dramatic 8 m rise in the Toce River at Candoglia and led to a river of water flowing through the streets of Brig resulting in great damage. Because of the complex mountainous nature of the region around Brig and the Toce River, high resolution atmospheric and hydrological models were needed to simulate accurately the distribution of precipitation and the resulting river flows. The models needed to be able to move parcels of air realistically up and down the topography and include the adiabatic and non-adiabatic processes leading to precipitation. In this example, the model was able to simulate flows over the terrain and the resulting precipitation patterns in good agreement with the observations from weather radars. When coupled with the high-resolution river flow model, the resulting stream flow was in good agreement with the observed 8 m rise in water level (Figure 5).

Another application of weather forecast models to broader environmental prediction is the prediction of air quality, typically of smog, and of other atmospheric contaminants. It has been traditional in air quality forecasting to only issue “alerts” or warnings when the atmospheric concentration of ground-level ozone or other pollutants was expected to exceed some pre-specified threshold. Studies of the effects of atmospheric pollutants on human health are now showing that some parts of the population are affected by much lower values and the concept of a threshold, below which there is no impact, appears invalid. When forecasts can be combined with a public education program, people can learn, through personal experience, how different levels of pollutants affect them and can adjust their activities accordingly. For this reason some governments are now issuing smog forecasts as an index that varies over some range and coupling this will with educational materials. An example of a two day forecast is shown in Figure 6. As our skill improves these predictions of smog will become more specific in location, type of pollutant and extend for longer periods. Since smog is exceedingly variable on the urban scale, particularly for coastal cities, very high resolution models (about 1 km resolution) will be needed. Interestingly, as forecasts become for skillful for longer periods (a few days) and people gain confidence in their predictions, there will be human responses, such as changing their activities to reduce their emissions of pollutant-creating chemicals, so that the forecasts will become incorrect.

Regional and urban smog is not the only atmospheric contaminant that is of interest for prediction. Another example is that of forecasting the tracks of dust from volcanic eruptions. Unfortunately, there are now several cases where high-flying jet aircraft have flown into “clouds” of volcanic dust, without realizing that is what they were encountering. The amount of dust in such clouds is sufficient to cause engine failure. By coupling information on amount, type and vertical velocity of plumes from volcanic eruptions with atmospheric model predictions, it is now possible to predict the position of volcanic dust plumes for days into the future and provide warnings to aviators (Figure 7). In the future, these predictions will be fully incorporated into aviation weather predictions and flight planning.

These are examples of what I call environmental prediction. They extend the forecast system beyond our typical domain of weather and involve the use of skills and information on the chemistry of the atmosphere as well as its physics. Another example would the predictions of stratospheric ozone layer depletion and its influence on the incidence of ultra-violet radiation at the surface. Again, predictions of UV radiation need to be coupled with public education information on the relationships between an index of UV radiation and human health (skin sensitivity). As we look to the future, we should see composite forecasts that bring together forecasts of weather, air pollution, UV indices, etc., with other variables as full environmental predictions for citizens, in a way that they can not only respond to but can, in some, cases, influence the result.

As a result, we will have comprehensive environmental prediction systems integrating expertise from a wide range of disciplines and addressing important issues in both research and operational prediction modes. Prototype coupled data assimilation and prediction systems are already under development in several countries based on combining components dealing with the atmosphere, oceans, waves, ice, chemical transport, hydrology and other aspects of the natural environment. There is of course a limit to the length of deterministic forecasts. It seems very unlikely that any breakthrough scientific idea or approach will allow us to predict beyond the predictability limit, which we generally think to be about two weeks. However, there have been exciting scientific advances that allow predictions of value beyond the butterfly effect. Instead of being deterministic, these are predictions of statistical quantities, probabilities, vulnerability and/or risk and use a variety of approaches will not be explored here. Suffice to say that the use of ensemble predictions methods will lead to even greater advances and skills in the future.

As we look beyond the seasonal to inter-annual predictions of climate variability, we can look to climate change, driven by a combination of human activities superimposed on natural variability. From a physical scientific point of view, it is appropriate to use the prediction scenario approach. Simplistically, this is "what if, … then". In order to undertake these predictions, it is necessary to build global climate models including the atmosphere, ocean and ice, land surface and biosphere in ways that simulate their role in climate variations and change. Building these models depends on understanding of climate which, in turn, is built on monitoring and understanding the past. In Figures 8 and 9 are shown examples of the simulations of global climate change corresponding to a scenario of greenhouse gas concentrations increasing in the future at a rate of 1% increase per year in the effective atmospheric concentration of carbon dioxide. Sulphate aerosol concentrations were also included because of their cooling effect on climate. For the first part of the simulation, to the present time, observed values were used.

Note that meteorologists are very good a monitoring the skill in numerical weather predictions but we are less good at evaluating and documenting the value of a forecast to the general public. Science and technology, working together, will lead to predictions of an unprecedented quality and resolution. By 2030, our model predictions will be indistinguishable from observations and this will open the possibility of many more products and services to all. As we look ahead to 2010-30, we can see weather forecasting evolving to physical environmental prediction, with models of the coupled atmosphere, land surface, hydrological cycle, cryosphere and oceans, together with chemical and bio-ecosystem elements. It is clear that NMHS should move into environmental prediction because there is the scientific basis and we have a strong operational approach that will make it a success.

## 2.3 Technology

Technological change over the past 50 years has been dramatic and we can expect it to continue and probably accelerate in the 21st century. Operational observing system technologies will evolve gradually, reflecting the required nature of rugged and operational technology and can take a decade or more to move from discovery to implementation within operational forecasting systems. Exciting possibilities in the future spaced-based observing systems will lead to an increased use of space-based and other remote sensing observing systems, providing for new opportunities to observe the state of the atmosphere and other parameters in globally consistent ways. However, they also evolve on decadal time scales for development and implementation. System-wide technology changes will continue to be incremental rather than precipitous due to the large capital investment in existing plant and equipment as well as the evaluation methodology that "proves" new operational capability prior to abandoning older technologies.

While technological change gives us new ways of making observations, increases in supercomputer power combined with dramatic decrease of cost will make higher resolution models for longer time periods and a greater array of parameters possible. In parallel with the advances in our scientific knowledge and modelling capabilities, there will also be rapid technological evolution leading to ever increasing supercomputer power. The globalization and revolution in telecommunications and related computer technology will present numerous opportunities as a new era for satellite-based radio-communications begins in the early part of the 21st century. Low earth orbiting satellite systems (socalled LEO systems) will provide low cost and efficient communications services almost independently of the national infrastructure. Rapid technological change increases the challenge of integrating new technology while, at the same time, maintaining networks and exchange of data and products.

NMHS need to take advantage of technological change through a coordinated program of research and development and capital planning. Implementation of technological change must be very carefully planned using an incremental approach. It is clear that implementation will be beyond capability of any one NMHS, when considered on a regional to global scale, and use of partnerships and alliances will be needed. One of our great strength is our history of working together. In the future regional and international alliances amongst NMHS will grow. There will also be increasing interactions with academia and the Secretariats of Multilateral Environmental Agreements and other emerging institutions.

Particularly in the media and information technology sectors, there should be a wide range of partners. As we look to 2010 and beyond, there will be changing relative roles of national versus international organizations in delivering information to citizens. The World Wide Web will play an increasing role. The future will require more collaborative approaches to observing systems, research and development and computing and telecommunications activities.

## 3. The Weather and Environmental Prediction Systems of 2010-30

The atmosphere is one component of our environmental system. Because of its time-varying nature and its role in driving change, it is natural to extend weather forecasting into physical environmental prediction, encompassing the atmosphere, components of the land surface, the hydrological cycle, the cryosphere and the oceans, with limited bio-ecosystem elements. This has already started in many countries and this trend should be extended. As we move further into the 21st century, we will evolve towards full environmental prediction, with full and interacting bio-ecosystems. Just as the scope of weather forecasting will be broader, weather services in the 21st century will become organizations that warn and inform their citizens and governments, on changes on a seamless time scale stretching from minutes to decades; e.g., warnings of minutes for tornadoes, days for winter storms and air pollution episodes, weeks for floods and droughts and decades for climate variations.

Our role should be that of a clear, science-based information source, providing information on the past, present and future states of the environment, in as broad a sense as is scientifically credible and within our mandate. We can best do this role in a “policy independent” mode; i.e., as an organization that inputs to the development of government policy but does not have a role in legislating nor enforcing environmental or related policy. Through predictions and reporting, we will provide the basis for both government and citizen decision making and adaptive response. We observe the state of the atmosphere and make predictions for 5 days (for regional air quality) or 50 years (for climate change). Based on the predictions, governments will work together to influence human activities and, hence, alter the prediction. Based on assumptions on the effectiveness of these interventions, we can then prepare a new prediction for 4 days or 40 years. The result is that part of the negative impact will be mitigated (not happen) but part will, since governments’ intervention will usually not be fully offsetting. Our predictive role will lead to effective government action to warn and inform citizens and governments so that corrective and adaptive actions can reduce the negative (and enhance the positive) aspects of atmospheric environmental change.

Weather services should not hesitate to extend themselves in this way. There is a scientific basis and also the strong operational, prediction service approach that does not generally exist in other organizations related to environmental issues.

Looking ahead to 2010-30, we can expect to see even more fully integrated observing-prediction-dissemination systems supported by research and development. The observing system will be designed to provide comprehensive atmospheric, hydrologic, land surface and oceanic data to meet the expanding needs of diverse client communities and will be responsive to the varying needs of prediction system, which in turn will be responding to real-time feedback and interaction from citizens and clients. As the systems are more integrated and extensive, there will be needs for large information flows that can only be accommodated through enhanced global telecommunications systems, using advances in satellites and fiber optic systems.

The focus of the national meteorological and hydrological services of the world should be on weather and physical environmental prediction to warn and inform our citizens and governments of changes on a seamless time scale stretching from minutes to decades and to provide a basis for sustainable development

The "seamless time scale" of warnings would extend from:

1. Minutes for tornadoes; to
2. Days for winter storms and air pollution episodes; to
3. Weeks for floods and droughts; to
4. Decades for climate variations.

Although I have emphasized the integrated nature of future weather and environmental prediction systems, it is still appropriate to consider the elements separately, while noting their interactions.

3.1 Observing Network Systems:

The future will be an "*integrated observing system*"; an optimized network designed to provide comprehensive atmospheric, hydrologic, land surface and oceanic data to meet the expanding needs of diverse client communities. This system will use multiple observing platforms to observe common parameters and integrate the results for ingestion into a variety of display and analysis systems. Derived fields will be displayed as required for various applications. There will be less reliance on single observing platforms. Through multi-use platforms, there will be efficiencies in observing systems. One area of real progress will be in the use of measurements by commercial aircraft. New sensors are being developed that will enable humidity measurements to join the suite of measurements that can be made and communicated in real time. In addition, special remotely-operated aircraft will be used extensively to fill data gaps in our observing system. These will be a key part of adaptive observing systems. A challenge will be the management, on an international basis, of the deployment of adaptive observing systems focusing on specific weather systems.

Measurements from space will continue to evolve and offer great potential for the future. The success of the Tropical Rainfall Measurement Mission, TRMM, an example of international cooperation, will be followed with the global precipitation mission, with an array of microwave sounding satellites, benchmarked by sophisticated rain radar in a high inclination orbit that will cover most of the globe. Significantly improved quantification of the global water cycle will be possible. The Integrated Global Observing Strategy, with all space agencies working together with NMHS and other agencies, should lead to a much improved global system. There will be more continuity and compatibility of measurements.

Unfortunately, global surface-based observing systems, over both land and the oceans, will still be quite varied in quality and, particularly, quantity. There will be need for continued mutual assistance to address these issues. A related question that needs to be addressed is the possibility of international management of special observing systems focusing on specific weather or climate systems.

The goal of the integrated observing system will be to collect, process and display a full three-dimensional description of the state of the physical environment at all locations, rather than only where we have in situ sensors. We can expect major changes in our data assimilation systems and, in particular, in the way they handle remote sensing data and high-temporal-frequency data. The optimum mix of observations clearly depends not only on the characteristics of the model in use, but also on how the data are assimilated into that model. The development of four-dimensional variational data assimilation will give a profound advantage in that the information from each observation is distributed in time and space using the model itself. Consequently, the influence of each observation will depend much more realistically on the situation than it does in present systems and more information about one variable can be extracted from observations of another

Observing systems will be designed to provide comprehensive atmospheric, hydrologic, land surface and oceanic data to meet the expanding needs of diverse client communities. We will see a continuing shift overall towards more remotely sensed measurements compared to in situ measurements. Within those in situ measurements there will be a shift towards further automated systems. Overall, these systems will provide an improved capacity to observe the atmosphere and other systems to input into forecasting systems. Particularly important will be the methods to integrate this information, in real time, into a variety of display and analysis systems. Following from these analysis systems will be the opportunity to have responsive observing systems that can be changed, augmented, etc., to special needs or focus on particular issues.

### 3.2 Prediction Systems:

There are truly exciting prospects for prediction systems in the next 20-30 years. With the developments in science and technology, it should be possible to push much closer to the limits of predictability. It is expected that forecasts of the skill we presently see for days 4 and 5 (see Figure 2) will extend out to nearly two weeks. These forecasts will have great social and economic value, for example, in terms of safety of travel and planning of economic activities. Several day forecasts of severe weather and related conditions which will provide earlier warnings and be focused to specific local populations and regions will result in reductions in loss of life and property. Beyond the predictability limit, ensemble prediction approaches will be used to provide statistical guidance for a month, a season and the next year. Inclusion of more extensive and accurate observations and models of the hydrological cycle will lead to improved forecasts of precipitation and all aspects of the hydrological cycle. With spatial resolution of 1 km or less and highly accurate predictions of winds, temperatures, etc., for several days, forecasts of severe weather will allow much earlier warnings to specific local populations, reducing loss of life and property.

Our capacity to manipulate large amounts of data from various sources will allow forecasters to see integrated data fields graphically in 4 dimensions. Models will only reach their full potential if the researchers and forecasters are working close together. Forecasters will identify priorities and gaps and the researchers will assist the forecasters in understanding the models and improving the science... a two-way continuous learning exercise that is science based

In analogy to our atmospheric predictions will be better will be global-scale oceanic predictions which will not only provide better lower boundary conditions for atmospheric models but be valid and important predictions of the oceanic conditions for fisheries management, marine transportation and other purposes.

In order to make these systems a reality, we will need to have a close working together relationship between the forecast and research communities. Forecasters need to be very much involved in identifying priorities and gaps. The research community needs to understand how it can (and must) work to assist forecasters in understanding and use of models and work towards improving the science. This need be a symbionic two-way continuous learning relationship between forecasters and researchers that is science based.

There are several practical issues that each country need to resolve to optimize its forecast production approach in order to gain the best benefits from these advances. One issue is the increasing capability for computer models to directly generate forecasts. What will be the role of the human? Clearly there will be a role for humans for the foreseeable future. It is not expected, nor acceptable, that forecasts can be delivered directly to citizens and clients. However, the role of the human needs to be optimized. Questions like “where and when to ‘intervene’?” need to be thought through and probably experimented with. For the forecaster to know better where and when to intervene, or more generally where to best use his or her time in having the best overall set of products, forecasters will have to have an excellent understanding of forecast models, so that they know their limitations and can focus on those in judging interventions. In the end, each country will need to make these decisions, based on their own circumstances, including the models they use and relative expenditures that are appropriate in people, technology and other costs. As we move into the future, it is expected that there will be a shift towards more automated forecast products (Figure 11).

The public and our clients will play an ever increasing role in defining both the means of delivery, performance standards and product quality assurance based upon the sensitivity of the user and their information needs. We should not assume that we know what is needed. There is great scope to products and services and it will be a matter of governmental policy as to where the balance of public good versus user pay rests. We expect to see:

- emergence of greater public education and awareness of forecasting, especially in how to respond to severe weather and environmental emergencies
- improved understanding of user requirements and ability to tailor products to the decision making criteria of various interests will be of increased importance resulting in forecasts that will move toward user-defined (in real time) products
- statements of forecaster confidence could become part of the forecasts
- computer generated products will become the norm for days 2-5 and beyond, while humans will continue to monitor and improve the day-1 public forecasts and warnings.
- graphical forecast products will gradually eclipse the current text based products

### 3.3 Forecasting and Dissemination

Within countries, there will be a need to make rationale decisions on whether to focus on national centres of expertise (extreme weather, aviation, agriculture, marine, etc.) with broad geographical responsibilities or on offices that provide forecasts for the full range of services for a specific geographical area. As computing power increases and becomes relatively less costly, more offices will be able to run specialized and sophisticated models. The approach taken in each country will need to consider the national variations in weather types, the skill and specialization of forecasters, telecommunications and political considerations.

Regardless of whether the forecast centre is local, national or international, there is a need for client and public service offices, probably using products from elsewhere, that must interface with the users of forecasts. Hence, there is a need for ways of delivering services, or dissemination systems.

In addition to the mix of human and machine generated products, there is the question of how countries should operate their forecast and dissemination offices. It has been traditional that weather offices were staffed and given responsibilities on a regional basis (Figure 12). Each office had the responsibilities for all forecasts and their dissemination, appropriate to the region. There are advantages in terms of the staff gaining familiarity with regional weather conditions and with the regional needs of the public and any special clients. The disadvantages are that each office needs to have a full complement of facilities and forecasters, which adds to the cost and may result in subcritical capacity. Further, as forecasting becomes more complex and specialized, it is difficult to have the range of forecast skills, all maintained, within each office.

Other approaches have also been implemented, such as the centralized and specialized forecasting models (Figure 13). In the centralized forecasting model, all forecasting is done in one office, while the other offices serve only as dissemination offices, i.e., where the forecasts are delivered to the public and other customers. The advantage of this is the economies of scale and efficiencies with staff. Only one set of facilities are needed and the staff can be more interactive and work on issues in a full team approach. The disadvantage, for larger countries, is the concentration of all forecasters in one location which may not be socially or politically acceptable. The forecasters also lose contact with the “local” weather since they all live in one location. The specialized forecasting model is a compromise between the traditional model and the centralized model. By having some or all offices specialize in a certain subject, such as public, aviation, marine or agricultural forecasting, the staff and the facilities can be focussed on a special topic, they can be trained and develop special expertise and the clients throughout the country have a single, common point of contact. The negative aspects are similar to that of the centralized forecasting model, in that forecasters are, for any given subject, all in one location.

If one looks beyond the typical country models, as above, then there is the possibility of cooperation regionally or multinationally (Figure 14). On the international scale, countries will need to examine the question of national versus multinational prediction centres. For more than 20 years, the European

Centre for Medium-Range Weather Forecasting has demonstrated outstanding leadership in the medium-range weather prediction; the benefits of working together are very clear. The International Research Institute for Climate Prediction, focusing on the El Nino-related interannual climate prediction, is an evolving example. How will these examples be followed into the 21st century? A borderless world with one tax base is not reality; but how and in which groups will countries agree to work even closer together. This usually means giving up some individual initiatives and compromising on priorities but leads to benefits. Another issue will be the position of those countries that do not naturally or for political or other reasons cannot fit into these multinational groupings. The next few decades will see these complexities stress our international cooperation and coordination and challenge our international institutions. There have been development of regional (multi-country) forecasting models such as the European Centre for Medium Range Weather Forecasting, where the decision is that one regional office makes all longer range forecasts, i.e., is a specialized forecast offices and national offices do shorter range forecasting and dissemination. Other examples include the Regional Specialized Meteorological Centres recognized by WMO and the International Research Institute for Climate Prediction (again using one forecast office for a special topic). Issues will be the proper balance of national and international initiatives and priorities. Overall, it is important that there be a continuing stress on international cooperation and coordination which will challenge to our international institutions.

### 3.4 Products and Services

A key issue for all weather services is how their governments decide to decide on what is "public good" and what is the role of the NMHS in the market place. There is essentially universal agreement that the provision of weather warnings, warnings for those events that could cause human suffering and possible loss of life, are a prime responsibility of governments. However, as the products and services range into general forecasts for the public to specialized services to special recipients, then there is a shift in thinking about what is "public good" and hence publicly funded from the general tax base to market place activities that should be funded by the recipients (Figure 15).

In the dissemination and use of weather and related-environmental information, there needs to be an ever increasing role of citizens and clients in defining means of delivery, performance standards and product quality assurance, based on their information needs. Weather services should be looking for greater cohesion between the originators of environmental information, end-users and policy makers. Products will be tailored to the decision-making criteria of various sectors which will result in forecasts of, inter alia, weather, climate or air quality to user-defined specifications.

Governments will have to be leaders in information and education and must assume the responsibility for making essential information available to the public for decision-making that contributes to economic well-being and protection of lives and property. We also need to make our information more complete and useful by including advice or guidance on how to use the information. As the public is being bombarded daily by information overload, an effective mechanism to synthesize the information and to communicate clearly will be essential. Considering these pressures, we will, by necessity, engage in mutually beneficial partnerships to deliver information.

Just as technological advances will greatly change the way in which we observe and predict the atmosphere, technological change is rapidly expanding the possibilities for dissemination of information. Although radio, television and print media will continue to be vehicles, the Internet and special systems for clients, such as direct to client cellular telephone, provide means of high-information flow that can also be interactive. Digital systems from constellations of satellites can provide graphical information of high resolution that is tailored to the recipient. There will remain the problems of delivering warnings and other information to communities that are technologically isolated.

As communication systems become more efficient and global, it raises the question of the relative roles of national versus international organizations in delivering information to citizens in any one country; this is already an issue and will become more complex and politically sensitive in the future. It is important that the role of the NMHS be understood and recognized, since it is often the visible delivery of a service that generates political and financial support to continue their key functions that lay the basis for global weather and environmental observational and scientific systems.

### 3.5 Performance measurement leading to service excellence:

As public expectations mount, weather services must be responsive with not only good products and services but also with published performance standards and measures of skill against those standards. In modern management terminology, there must be organizational commitment to "Service Excellence" coupled with broadly based "client feedback". As part of this, there should be statements of "forecaster confidence" for both the public sector and special clients.

We have seen recent statements of commitment by Governments and their institutions to be a leader in information technology; to ensure that essential information is available to its citizens; to improve public education and awareness; and to incorporate the use of our information in decision-making on various time scales by policy makers. These initiatives are ideal for the weather services to become leaders in, this is what we do.

### 3.6 People

People, our staff, are and will continue to be our greatest asset. Weather services must support the development of value-added people skills for all managers in order to maximize the effectiveness of staff and build a team approach. This will require innovative human resources management with encouragement of personal learning plans. With the evolution of our discipline and the increasingly complex challenges of the future, there is now and will continue to be, at an accelerating level, there need to continuous upgrading of staff. We will need investment in broader client-centred consultation, development of skills in marketing and taking an overall team approach to work.

I also expect that we will see increasing mobility of staff between academia, the private sector and public institutions. Related to this will be strategic recruitment and cross training among staff. As we move into environmental prediction, there will be an increasingly multi-disciplinary environment with cross-pollination of ideas and disciplines, encouraging and facilitating innovation and teamwork. With these approaches we will have success in promoting a healthy and productive workplace.

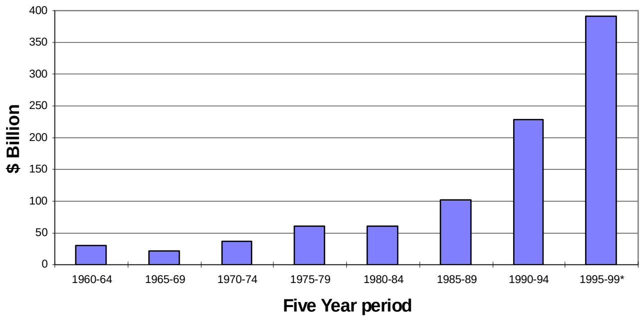
## 4. Concluding Remarks

The next 20-30 years present an exciting challenge to us (meteorologists, hydrologists, researchers and technologists) because both the tools and skills sets are expanding for the collection, production and delivery of environmental products and services. We will work towards a continuum of forecasting today's weather to next century's climate (Figure 16). For WMO and the community of national meteorological-hydrometeorological services, it will be a considerable challenge in international cooperation and in enhancing capabilities across all. Picking up this challenge represents a considerable step towards a sustainable future - a 21st century destination, reached via a partnership of "international cooperation", a consistent "environmental vision" and "science". Pre-requisite to living this future is the need to establish a communal path forward; to have the foresight to make timely decisions; and to take actions nowh to bring awaiting opportunities into reality.

### Further readings:

Powell, Douglas, and William Leiss, 1997: Mad Cows and Mother's Milk, The Perils of Poor Risk Communications. McGill-Queen's University Press, Montreal & Kingston, 398 pp.

Board on Atmospheric Sciences and Climate, National Research Council, 1998: The Atmospheric Sciences Entering the Twenty-First Century. National Academy Press, Washington, 364 pp.



Direct Global Economic Losses
Due To Major Natural Disasters

Source: Munich Re (constant 1998 $US)
* tentative

Figure 1. Global Economic costs of natural disasters, for 5 year periods, in $US Billion. Most of these costs are due to weather or weather-related events. In 1998 alone, the economic costs of weather-related disasters were about $US 90 Billion.

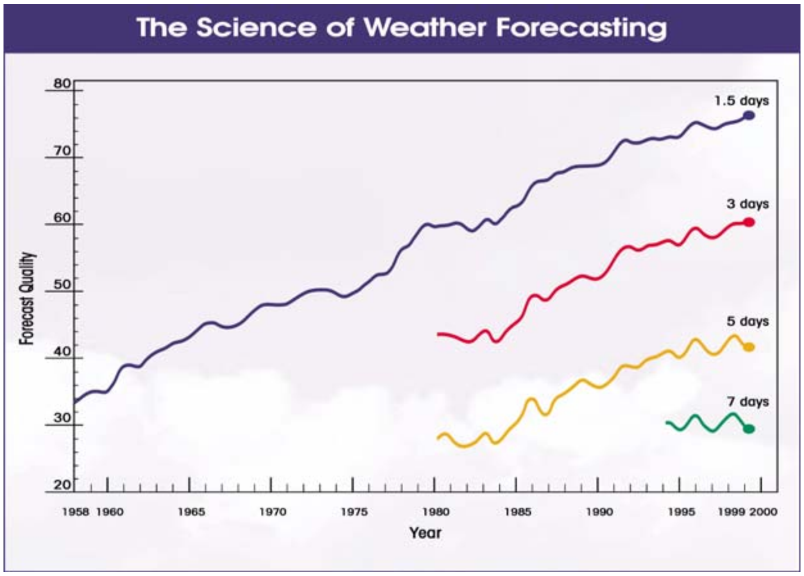


Figure 2. Skill in predicting the 500 mb pattern, as an example in the improvements in forecast skill. Example from the Meteorological Service of Canada. Trends in skill from other major centres would be similar.

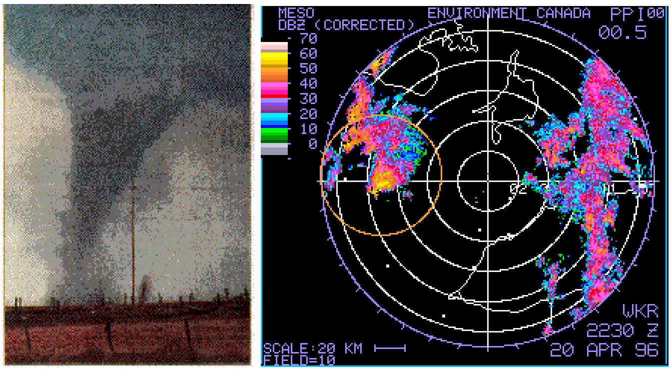


Figure 3. Mesocyclone Detection of April 20, 1996, Williams Lake Tornado.

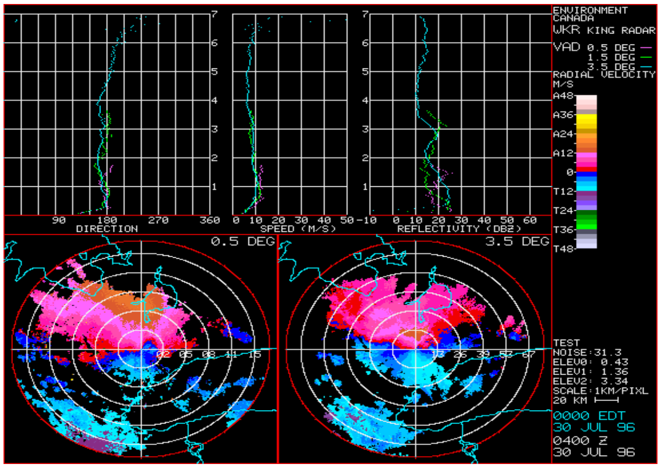


Figure 4. Wind profiling for storm detection and input to numerical weather prediction.

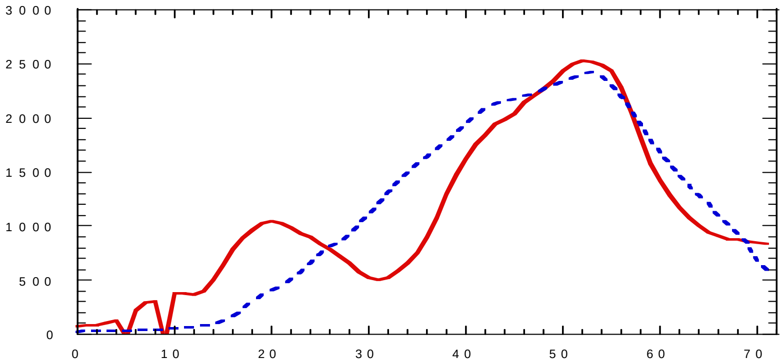


Figure 5. Observed and modelled river level rise on the Toce River using the 72 hours precipitation accumulation from the Canadian mesoscale atmospheric model on a 10 km grid, coupled with a hydrological model (Watflood) on a 2 km grid.

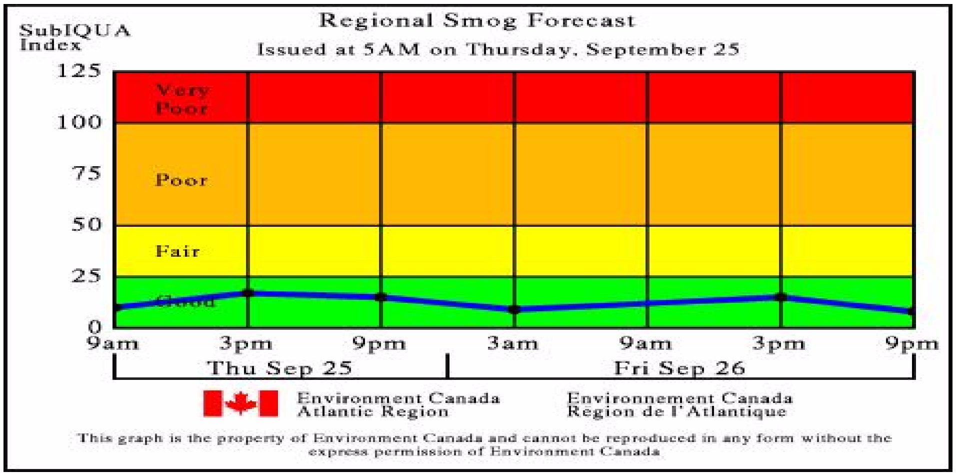


Figure 6. An example of a two-day forecast of smog for Atlantic Canada. These forecasts are combined with public educational material.

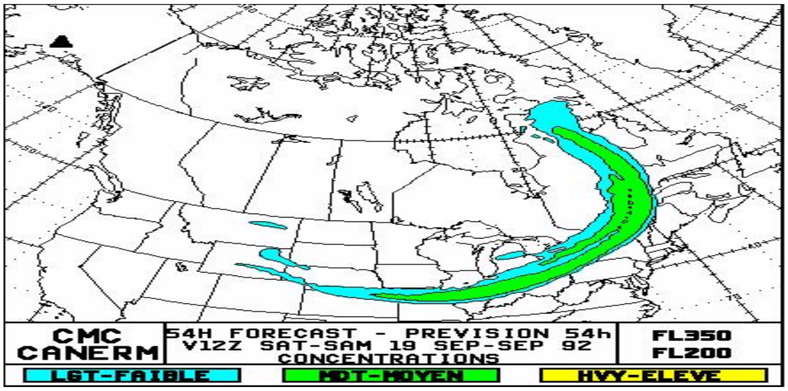


Figure 7. Example of a 54 hour forecast of the location and concentration of a volcanic ash plume, form a volcanic eruption over Alaska (see triangle in upper left corner).(Example from the Canadian Meteorological Centre of the Meteorological Service of Canada).

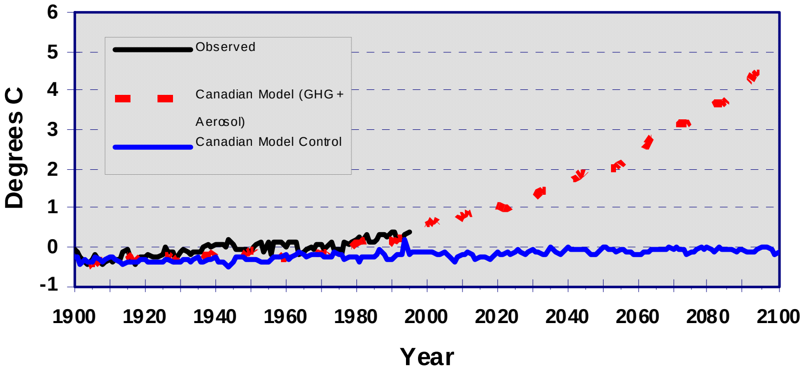


Figure 8. Observed and modeled globally-averaged surface temperature change. The combined effects of projected greenhouse gas and sulphate aerosol increases. Example from the global climate model simulations by the Meteorological Service of Canada.

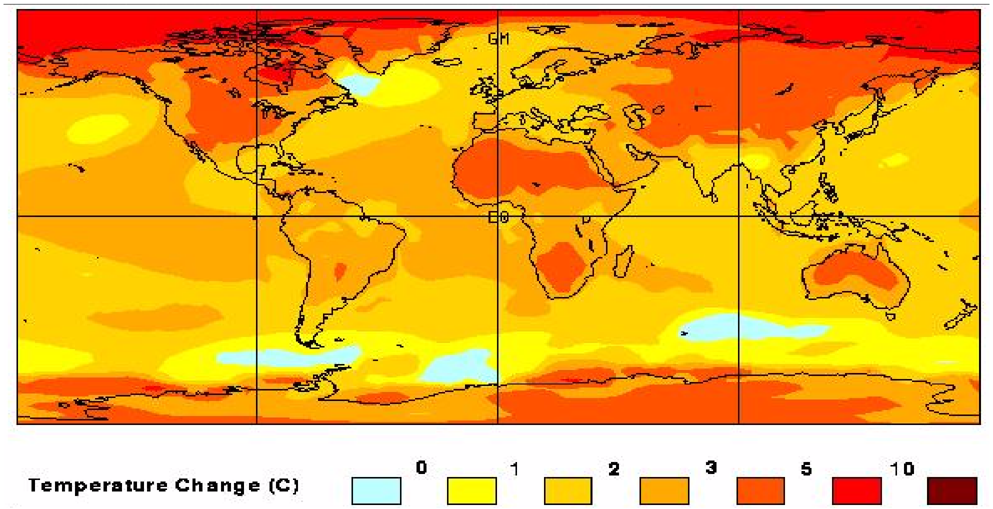


Figure 9. Projected surface temperature change between 1910 and 2040 AD, corresponding to Figure 8. The combined effects of projected greenhouse gas and sulphate aerosol increases. Example from the global climate model simulations by the Meteorological Service of Canada

# Observing Systems

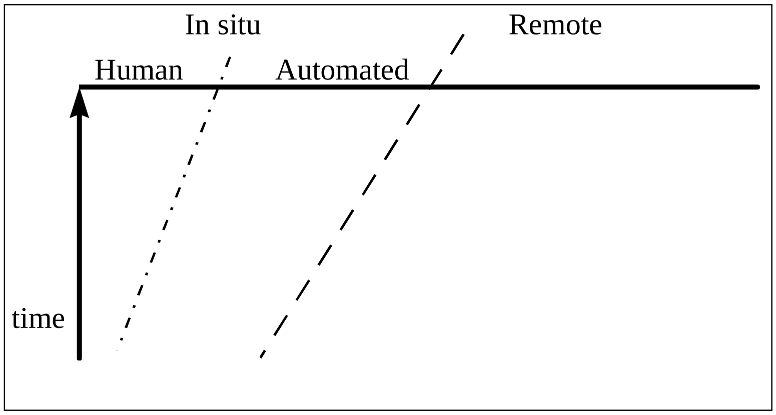


Figure 10. Trends in the mix of observing systems, with time. There will be increasing percentage of systems using remote sensing compared to in situ measurements, and within the in situ measurements, an increasing percentage of automated systems.

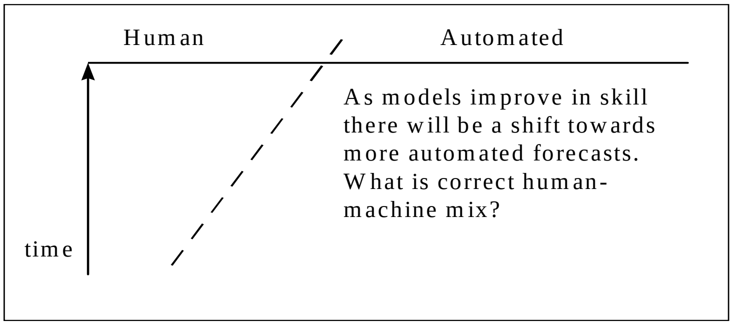


Figure 11. Preparation of Forecasts: the mix of humans and machines.

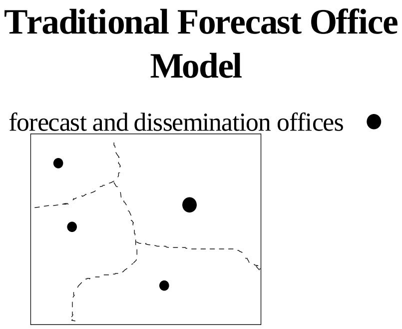


Figure 12. The traditional forecast office model where each office has responsibility for all forecasts and their dissemination on a regional basis.

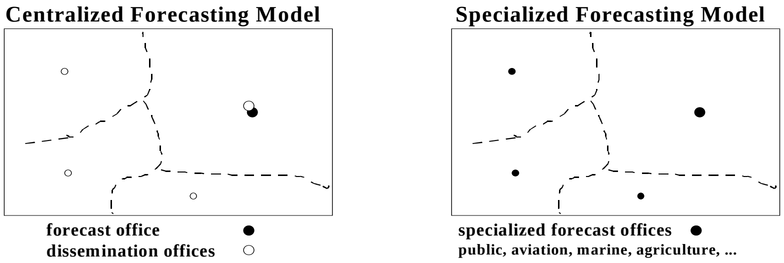


Figure 13. Two other models of forecasting are the centralized and specialized forecasting models.

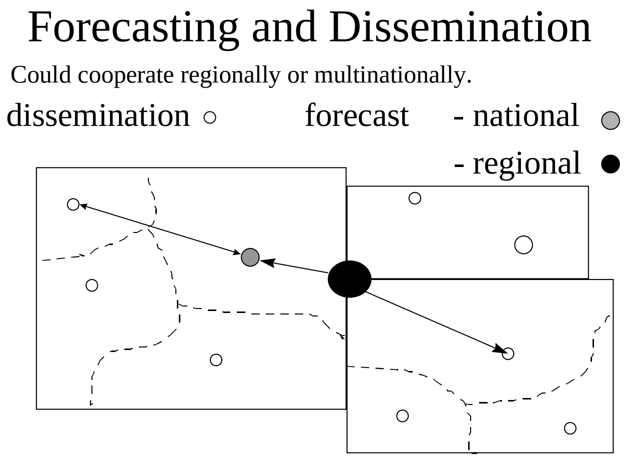


Figure 14. Cooperation across national boundaries leads to other forecasting model options, where some offices are solely for dissemination, some are specialized forecast offices and one or more are for the whole multi-country area.

Products and Services

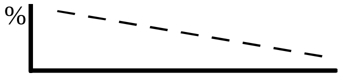
| Public Good | | Market Place |
|---|---|---|
| - NMHS | | - NMHS<br>- private sector |
| Warnings | Public services<br>- forecasts<br>- information<br>- to all | Special services<br>- forecasts<br>- information<br>- to recipients |
| |  | |

Figure 15. The distribution of products and services, from public good to market place activities.

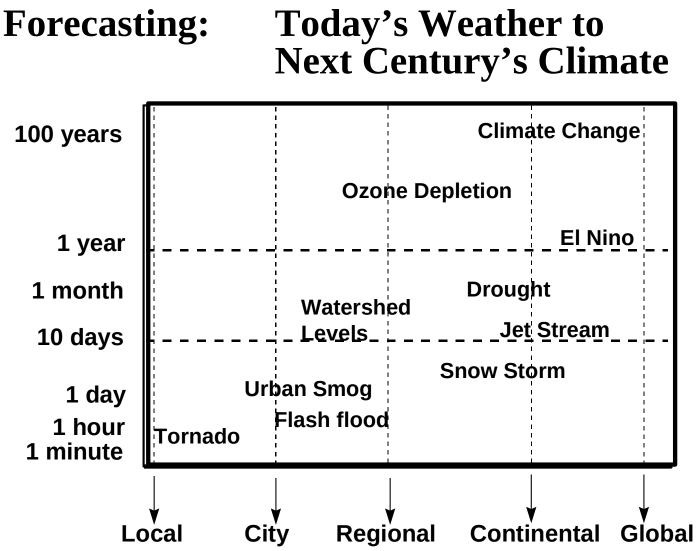
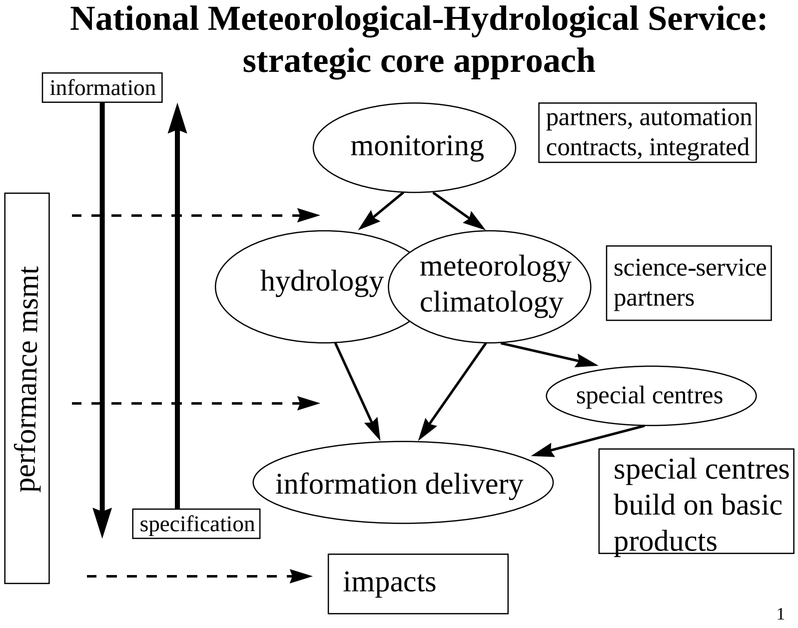


Figure 16. A continuum of forecasts - from toady's weather to next century's climate and covering the spectrum of physical environmental prediction.



Appendix Figure: Schematic of strategic core approach of NMHS