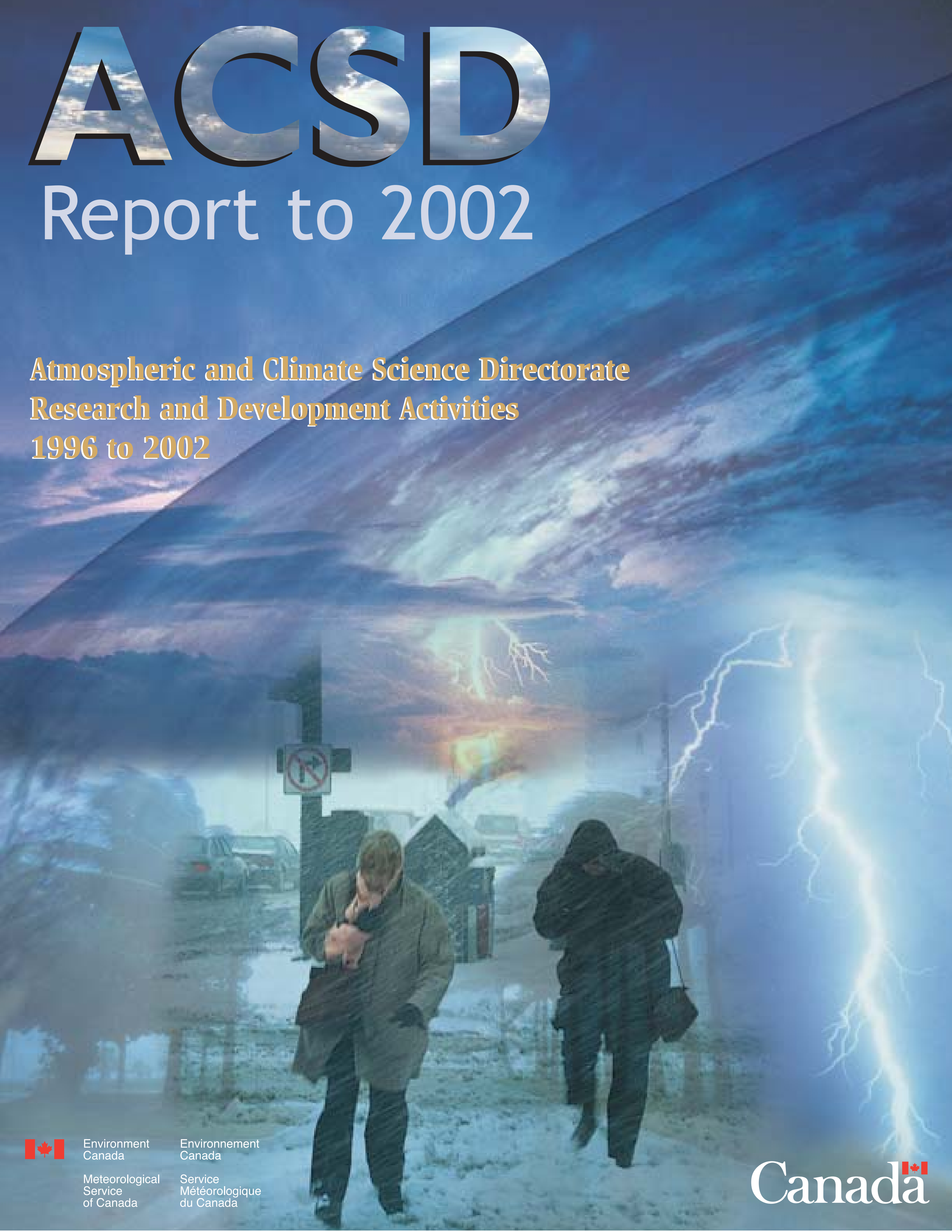
ACSD

Report to 2002

Atmospheric and Climate Science Directorate
Research and Development Activities
1996 to 2002



Environment Canada | Environnement Canada

Meteorological Service of Canada | Service Météorologique du Canada

Canada

The ACSD Management Committee

Left to right, front row: M. Phillips, K. Puckett, J. Masterton, MD. Everell, D. Whelpdale, B. Bass;
Back row: M. Shepherd, J. Abraham, M. Béland, R. Street, L. Grittani.

We acknowledge with appreciation the directors and staff who played a role in putting this report together for a job well done. Special appreciation goes to Victoria Hudec, Stu McNair, Adam Fenech and Rebecca Williams.

Design and graphics by BTT Communications.

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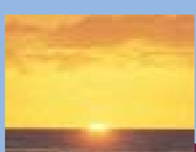


Message from the Director General

Dr. Michel Béland,
Director General,
Atmospheric & Climate
Science Directorate

I am pleased to make available to you this report on the research and development activities of the Atmospheric and Climate Science Directorate (ACSD) of the Meteorological Service of Canada (MSC). The report covers activities over the period 1996 to 2002. We made the decision to cover accomplishments over the past five years or so; firstly, because this is the first report of its kind and secondly, because it very often takes quite a number of years for a research project to reach maturity. Thus, a five-year repeat time for an extensive report such as this one is perhaps appropriate. However, we are planning to produce shorter intermediate reports on a yearly basis to cover highlights.

We have had quite a number of exciting science activities over this period, as you will no doubt be able to see for yourself in going through this report. Rather than try to summarize this in this message, let me draw your attention to a major event which happened over the last year or so, namely a major peer review of all MSC Science programs. The review was conducted by an international 15 member blue ribbon panel, chaired by Dr. Joe Friday, of the US National Academy of Sciences (its report is available, on-line on the ACSD website, or in hard copy upon request).

I am very proud to announce that the main conclusion of their report is that the MSC Science program, and particularly the ACSD component, is meeting the needs of Canadians with a high level of excellence (ACSD was deemed a world leader in some areas, and world class in many others). We were also acknowledged for meeting most of the guidelines and principles of the SAGE (Science Advice for Government Effectiveness) report. I believe the strength of the ACSD program is due to the excellence and dedication of its staff. It is clear that they have successfully met the many challenges, scientific, organizational, political and financial with energy, creativity and commitment. And so I would like to take this opportunity to let our staff know the deep appreciation that my management colleagues and I have for their contributions.

The challenge, of course, is to forge a path into the future that will maintain this level of performance. The environment in which ACSD will be operating in the next 5 to 10 years will certainly be quite different from the one it has known previously. For example, the role of Canadian academia in atmospheric sciences is increasing markedly, due in part to a recent sizeable increase in funding. The environmental issues, as well as the weather services obligations that science will need to address are themselves evolving rapidly (climate change, pollution, water scarcity, ensemble approach to NWP, remote sensing, etc.). The funding pressures that MSC is facing, like many other government organisations, will warrant very careful strategic choices. And finally, the 'graying' of part of our scientist population, and the associated 'thinness' of some of our program staffing will need to be resolved.

We are now going through a major management re-engineering exercise in the Meteorological Service of Canada. At the same time, our government is also re-examining the way it conducts science business and its funding activities. We will be working very hard, within the context of these exercises, to come up with a winning strategy for the MSC science activities. My personal objective is that when we call in the next peer review exercise, either myself, or my successor will be writing words that are as positive as those I was able to write in the beginning of this message. I am optimistic that we can achieve this, and in the meantime, I hope that you will enjoy reading or browsing through this report.

In closing, I would like to express my thanks to all those who contributed to this report, managers and scientists alike, and to my office staff who had the (sometimes) ungrateful task of pulling it all together; my special thanks also to Vicky Hudec who took special care of the graphics, formatting and editing of this report.

Michel Béland

Introduction

In the fall of 2001, the Meteorological Service of Canada (MSC) undertook a comprehensive external peer review of its research and development (R&D) activities spanning over five years. This report, *Atmospheric and Climate Science: Report to 2002,* captures highlights of research and development from 1996 to 2002 and is intended for government science and technology (S&T) managers, university department heads and other environmental research organizations. The comprehensive nature of the report also makes it suitable as an orientation document for anyone interested in the MSC's atmospheric and climate research program, including potential staff, collaborators and visiting scientists.

A companion report titled, *Atmospheric and Climate Science in the Meteorological Service of Canada : Research Making a Difference*, is also available. This is a shorter document that focuses on MSC's and the Atmospheric and Climate Science Directorate's (ACSD) most significant R&D accomplishments over the past several years, and specifically the impacts that this work has had on external users, including policy makers, regulatory agencies, international science programs, and Canadians. *Research Making a Difference* is intended for a broader audience and showcases atmospheric and climate R&D from the perspective of those benefiting from the results.

MSC Strategic Research

R&D within Environment Canada (EC) is focused on supporting the department's priorities, which are set in the context of the mandate of the federal government and its initiatives. R&D is managed in the same manner as other departmental activities. Four primary business lines; Nature, Clean Environment (CE), Weather and Environmental Predictions (WEP), and Management, Administration and Policy (MAP) provide the structure within which the department operates.

Two of these business lines, Clean Environment (CE) and WEP are of particular importance to ACSD since they represent the strongest ties to departmental priorities. The research agendas for these two business lines are summarized in the following sections.

WEP Research Agenda

The outcome and key results to be accomplished by the Weather and Environmental Predictions business line are described in the following table:

Weather and Environmental Predictions – Results	
Business Line Outcome:	Adaptation to influences and impacts of atmospheric and related environmental conditions on human health and safety, economic prosperity and environmental quality.
Key Results:	Reduced impact of weather and related hazards on health, safety and the economy. Adaptation to day-to-day and longer term changes in atmospheric, hydrologic and ice conditions.

Research supported by the WEP business line provides the scientific knowledge and understanding of the physics and chemistry of the atmosphere that form the scientific basis for Canada's weather forecasting and warning capabilities, and the development of policies on climate change, clean air, stratospheric ozone depletion and water resources.

The key results described in the preceding Weather and Environmental Predictions 'Results' table are through R&D in each of the following areas:

1. **Meteorology and Hydrology** – Reducing impacts of summer and winter severe weather through improved detection and more accurate and timely prediction.
2. **Climate** – Reducing uncertainties of future climatic conditions through improved measurement and modelling.
3. **Atmospheric Chemistry** – Improving policy development and air quality forecasts through a better understanding of the spatial and temporal distribution of pollutants, their formation, transport, transformation and deposition, and the effects of atmospheric pollutants on health and ecosystems.

4. **Adaptations and Impacts** – Developing adaptation strategies through identification and assessment of potential ecological and socio-economic impacts resulting from meteorological (climate, air quality and weather) stresses.
5. **Science Assessments** - Integrating and applying research to strengthen decision making, including policy development and the negotiation of agreements, and communication.

Two crosscutting issues that are tied to these results include making **effective use of the explosion of observational satellite data** becoming available; and **fully integrating environmental prediction models** that combine multiple processes (biological, chemical, physical, hydrologic, etc.) on varying temporal and spatial scales.

The MSC R&D International Peer Review Panel identified ACSD's limited critical mass of people, facilities and financial resources as a barrier to achieving the key results required to maintain a strong, vibrant position within the research community. In particular, the panel cautioned in allowing increases in 'soft money' as this dilutes the focus and effectiveness of the research mission.

Clean Environment Research Agenda

The outcome and key results for the Clean Environment business line are summarized in the following table:

Clean Environment – Results

Business Line Outcome:	Protection from domestic and global sources of pollution.
Key Results:	Adverse human impacts on the atmosphere and on air quality are reduced. (Air Result) Environmental and human health threats posed by toxic substances and other substances of concern are prevented or reduced. (Toxics Result)

The Clean Environment Research Agenda links R&D activities with key results from the Clean Environment business line, and highlights the main priorities over the next few years.

The **Air Result** described in the Clean Environment 'Results' table can be divided into the following five sub-results:

1. **Climate Change** – Reducing greenhouse gas emissions.
2. **Air Quality** – Improving air quality.
3. **Acid Rain** – Reducing acid deposition.
4. **Hazardous Air Pollutants (HAPs)** – Reducing domestic and long-range transport of HAPs.
5. **Stratospheric Ozone** – Recovery of the ozone layer.

Within the five air sub-results, climate change and air quality are the highest priorities.

The **Toxics Result** can be divided into the following three sub-results:

1. Existing substances – Prevent or reduce adverse impacts on human health and the environment from existing substances of concern and ensure that these impacts are understood by Canadians.
2. New substances – Prevent or reduce adverse impacts on human health and the environment from new substances and ensure that new activities are understood by Canadians.
3. Virtually eliminate persistent, bioaccumulative toxic (PBTs) substances.

Within the three toxics sub-results, existing and new toxics are the highest priorities.

Organization

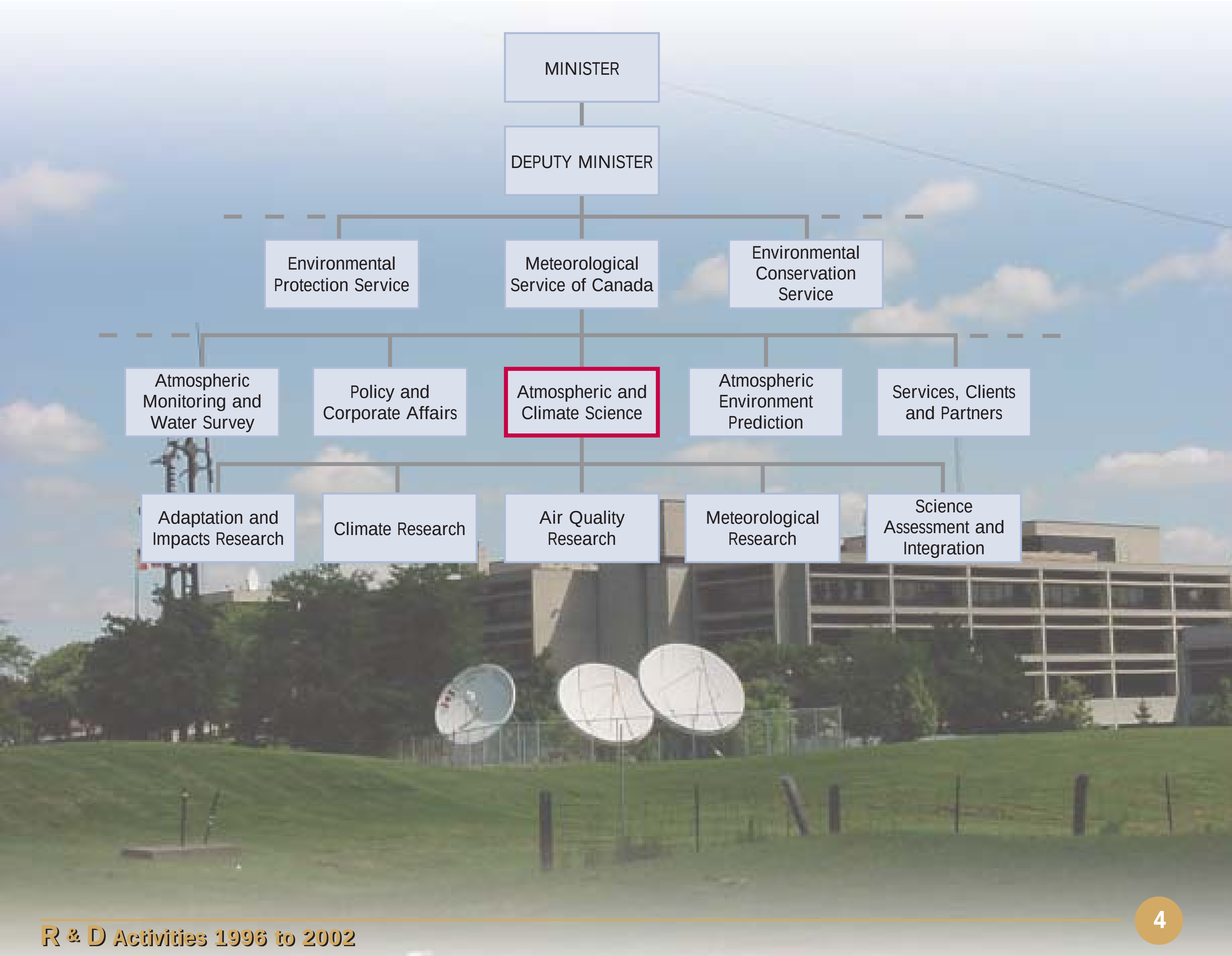
The Atmospheric and Climate Science Directorate (ACSD) is the focal point for atmospheric and climate R&D in Environment Canada's (EC) Meteorological Service of Canada (MSC). ACSD's Director General provides functional leadership for R&D activities. ACSD research can be broadly categorized into the following disciplines:

- Meteorology
- Climate
- Air Quality
- Adaptation and Impacts

In addition to performing and coordinating research, ACSD plays a role in integrating and assessing current atmospheric issues for the benefit of policy developers and other decision-makers in the MSC and EC.

The organizational structure of ACSD closely parallels these primary disciplines, with cross-cutting issues handled by a management committee with representation from each of the organizational components.

The following figure describes the organizational structure of Environment Canada.



Director General's Office

The Office of the Director General provides strategic planning and research policy development for the Directorate, and direction and coordination of Branch financial and human resources activities, such as the research scientist promotion process.

The office represents ACSD on MSC and EC Management Tables and Boards and on collaborative initiatives with external agencies. It manages the Visiting Fellowship Program, the MSC Scholarship Program, the Industrial Research Chairs Program, and youth employment programs.

Climate Research Branch

The Climate Research Branch (CRB) provides the science in support of policy development and decision-making on issues of climate and climate change. The Branch's research is primarily in the following areas:

- Global and regional climate modelling and analysis;
- Cold climate systems processes and observational techniques;
- Atmospheric & oceanic global climate circulation patterns; and
- Climate data analysis and interpretation.

CRB's activities are directed at understanding the climate system by investigating key processes; modelling the climate system; and assessing the current state of climate.

Air Quality Research Branch

The Air Quality Research Branch (AQRB) provides the scientific basis for policy development and air quality services designed to reduce harmful effects of atmospheric pollutants on the environment and human health. The Branch's research addresses the following issues:

- Smog;
- Acid deposition and oxidants;
- Hazardous air pollutants;
- Stratospheric ozone; and
- Greenhouse gases & climate change.

AQRB conducts systematic measurements, develops air quality models, and initiates special studies in order to understand the emission, transport, transformation and deposition of atmospheric pollutants across a wide range of spatial and temporal scales.

Meteorological Research Branch

The Meteorological Research Branch (MRB) provides the science that is needed to improve weather and environmental predictions. Research areas include the following:

- Severe weather;
- Atmospheric processes;
- Remote sensing; and
- Numerical weather prediction.

MRB's research focuses on integrating information from surface and remote weather sensors into numerical weather prediction models to support improved forecast techniques and the timely and accurate detection and prediction of severe weather events.

Adaptation and Impacts Research Group

The Adaptation and Impacts Research Group (AIRG) conducts research on the impacts of climate, air quality, and weather on human health and safety, economic prosperity and environmental quality. The Group's research addresses:

- Human health and safety;
- Socio-economic systems and communities;
- Sustainable development; and
- Natural ecosystems and water resources.

The Group works in close partnership with universities and a wide variety of stakeholders to develop new approaches for the evaluation of adaptation options and strategies.

Science Assessment and Integration Branch

The Science Assessment and Integration Branch (SAIB) identifies key scientific developments and communicates this information to policy developers and other decision-makers in a relevant manner. SAIB's primary activities include:

- Integration of relevant scientific developments across disciplines;
- Assessment of the state of science; and
- Communication of science to non-scientific audiences, policy makers, and stakeholders, and provides relevant feedback to the scientific community.

The branch works closely with the regions and other services of Environment Canada, other government departments and stakeholders, and actively represents Canadian research internationally.

Resources

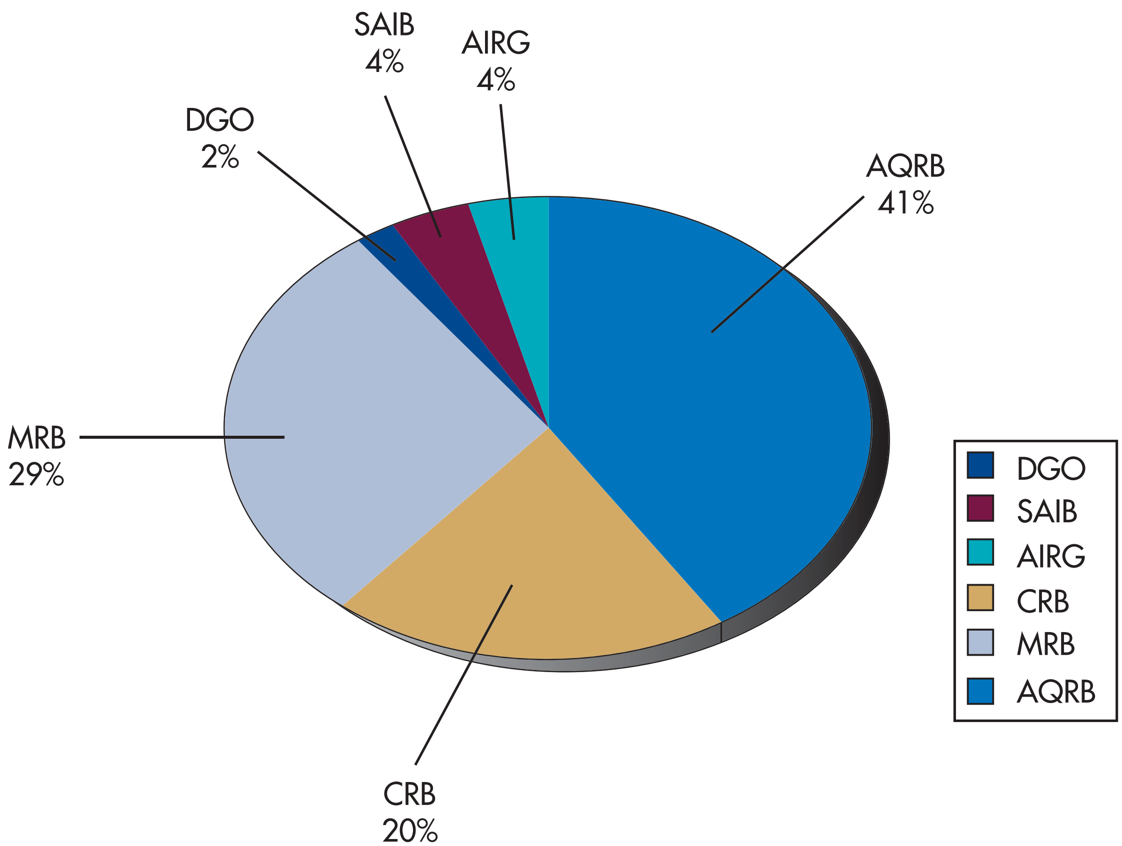
The primary source of funds for ACSD research is the WEP business line, providing approximately 75% of all salary and operating resources. The Clean Environment (CE) business line provides approximately 9% of total funding, although CE funding represents just below 50% of AQRB resources.

The remaining 7% of funding is primarily from other federal government departments and programs (5%), including the Program for Energy Research and Development (PERD), the Department of National Defence (DND), Transport Canada (TC) and the Canadian Space Agency (CSA), and from external sources (2%), including licensing revenues.

Atmospheric and Climate Science Directorate (ACSD)
FUNDING BY SOURCE

Funding Source	Salary %	Operating %
WEP	83	70
CE	15	26
Other government	2	4

The distribution of resources within the Atmospheric and Climate Science Directorate (ACSD) is as follows:

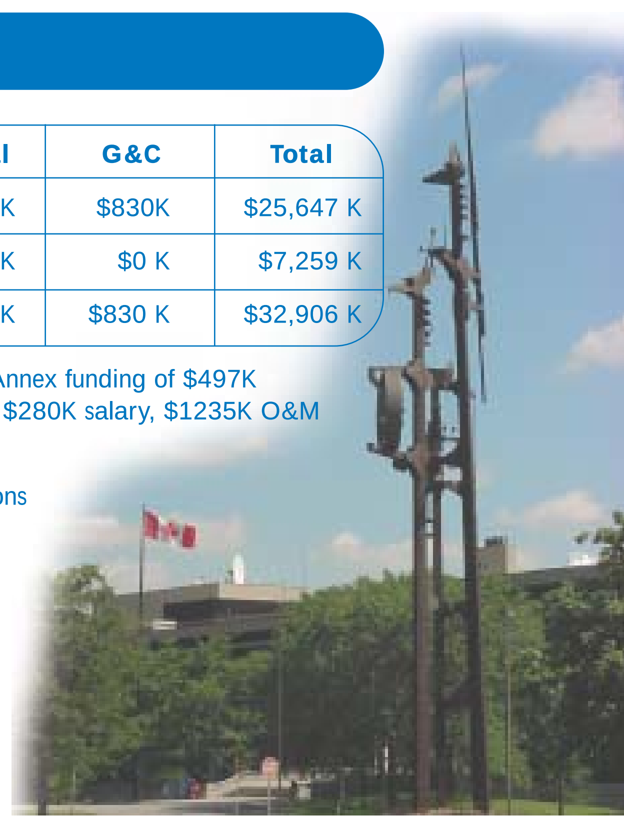


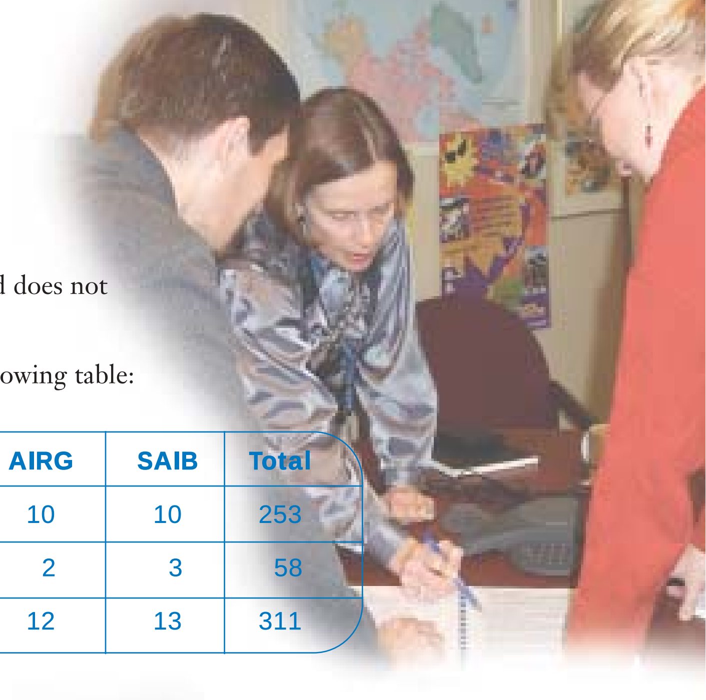
Atmospheric and Climate Science Directorate (ACSD)
2002-03 BUDGET ALLOCATIONS

Business Line	Salary	O&M	Capital	G&C	Total
WEP	$14,037 K	$9,558 K	$1,222 K	$830K	$25,647 K
CE*	$2,901 K	$3,650 K	$708 K	$0 K	$7,259 K
Total	$16,938 K	$13,208 K	$1,930 K	$830 K	$32,906 K

*Includes Acid Rain Business Case funding of $703K and Ozone Annex funding of $497K salary, $626K O&M and $485K capital. CCAF money received is $280K salary, $1235K O&M and $85K G&C

O&M- Operating and Maintenance, G&C –Grants and Contributions





Staff

ACSD staff totals approximately 311 people. The number fluctuates and does not include visiting scientists, visiting fellowships (21) and students (14).

The breakdown of staff for 2002 by organizational unit is shown in the following table:

Staff	DGO	MRB	CRB	AQRB	AIRG	SAIB	Total
Indeterminate	5	70	51	107	10	10	253
Term	0	15	12	26	2	3	58
Total	5	85	63	133	12	13	311

Publications

ACSD research is published through a wide variety of channels, including government publications, technical reports, Fact Sheets, websites (Internet and Intranet) and through peer reviewed scientific journals and publications.

The most widely accepted form for research publications is the scientific literature – peer-reviewed journal publications. The following tables summarize ACSD's peer-reviewed publications in atmospheric and meteorological journals over the past three years. The numbers underscore the high quality and productivity of the research undertaken by the Directorate.

The total number of ACSD peer-reviewed journal publications, by year was:

ACSD Peer-reviewed Journal Publications in Atmospheric and Climate Sciences
1999-2001

2001	203
2000	162
1999	147

Not all the papers submitted in 2001 will actually be published in that year. A number of them could appear in journals in 2002.

Over the period 1999-2001, the total number of papers published (or submitted, in the case of 2001), by Branch for the three major branches were:

Branch Peer-reviewed Journal Publications in Atmospheric and Climate Sciences
1999-2001

AQRB	233
CRB	166
MRB	124

The numbers above include 11 cross-branch publications (AQRB-CRB 3, AQRB-MRB 6, CRB-MRB 2).

Over the period 1999-2001, ACSD scientists published 512 (this figure does not include papers that were submitted in 2001) in 108 peer-reviewed journals. The top six journals were:

Top Six Peer-reviewed Journal Publications in Atmospheric and Climate Sciences BY JOURNAL, 1999-2001

Journal of Geophysical Research	85
Atmosphere-Ocean	31
Atmospheric Environment	27
Environmental Science and Technology	25
Monthly Weather Review	23
Geophysical Research Letters	23

The Adaptation and Impacts Research Group (AIRG) of the Atmospheric and Climate Science Directorate (ACSD) conducts research in the socio-economic field of atmospheric and climate science, and their peer-reviewed publications are included separately below.

AIRG Peer-reviewed Publications 1999-2001

2001	23
2000	6
1999	23

The Science Assessment and Integration Branch (SAIB) of the Atmospheric and Climate Science Directorate (ACSD) conducts assessments of current scientific knowledge to address policy issues. These major undertakings involve years of co-ordination and report writing.

Science Assessment and Integration Branch

SCIENCE ASSESSMENTS	
1996 - 2001	11
PEER-REVIEWED PUBLICATIONS	
1999-2001	14

Clients

The *Key Results* and *Outcomes* of Environment Canada's business lines, and the priorities of the Department's research agendas serve to focus R&D on specific issues. These priorities are generally established to support policy development and service delivery. Policy development includes negotiation of domestic and international agreements and protocols.

Programs that benefit from ACSD's R&D and science assessments include the following:

ORGANIZATION/AGREEMENT	BENEFIT FROM ACSD'S R&D
Meteorological Service of Canada (MSC)	MSC's Regions and Canadian Meteorological Centre (CMC) draw heavily on ACSD R&D to provide services to the public, and aviation and defence clients.
Environment Canada (EC)	EC, and other government departments make direct and indirect use of ACSD R&D for a wide range of issues and services, including environmental emergencies, the Canadian Environmental Protection Act, climate change, and the management of toxic substances.
Canadian Council of Ministers of the Environment (CCME)	CCME, and other federal-provincial and multi-stakeholder organizations, benefit from continued ACSD R&D for several programs, including Canada-Wide Standards (CWS) and air quality indexes, forecasts and advisories.
International Joint Council (IJC)	IJC draws on ACSD research for scientific understanding and to develop monitoring and reporting protocols for agreements including the Great Lakes Water Quality Agreement.
Canada-US Air Quality Agreement	Negotiation of agreements and development of implementation plans and assessments for acid deposition and, more recently, transboundary transport of PM, ozone and precursors draw heavily on ACSD R&D.
Intergovernmental Panel on Climate Change (IPCC)	Makes use of ACSD's climate modelling capability to conduct scenario runs and it turns to ACSD scientists as contributing and lead authors for assessments.
Commission for Environmental Co-operation (CEC)	CEC, and other tri-lateral organizations, like NARSTO, depend on ACSD R&D for development of action plans, like the North American Regional Action Plan for Mercury, and for collaborative research projects.
United Nations Economic Commission for Europe (UN-ECE)	UN-ECE and other international organizations, including the Arctic Council, benefit from ACSD R&D in the development of protocols and monitoring programs dealing with issues including long-range transport of pollutants.
World Meteorological Organization (WMO)	WMO programs, including several observing networks, like Global Atmosphere Watch (GAW) and Global Climate Observing System (GCOS) make use of ACSD R&D and expertise to achieve their mandates.

Collaborations

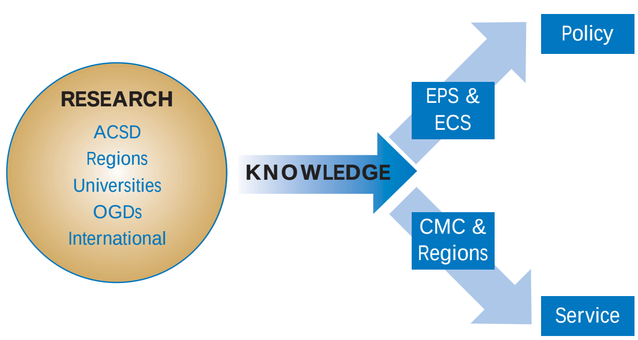
In order for a research organization to be world-class and to maximize the knowledge gained from a limited investment of resources, it is essential to forge meaningful and productive collaborations with other researchers and organizations around the world. By its very nature, atmospheric and climate research is of interest around the globe. There are significant benefits to be gained from promoting and participating in collaborative research efforts, both domestically and internationally.

Some of ACSD's scientific collaborations are noted below:

COLLABORATOR	BENEFIT FROM ACSD'S R&D
Universities	Collaboration on research priorities and graduate studies. Many ACSD research scientists are graduate student supervisors, adjunct professors, or have other teaching responsibilities with universities.
Other Environment Canada Services	Collaboration among the three Services (EPS, MSC, & ECS) for priority setting, policy development, international negotiations, method development and use of facilities and expertise.
Environment Canada Regions	Collaboration with regions on priority setting, program development, research projects, measurement programs, publications, and service delivery.
Other Government Departments	Collaboration on management and definition of projects, preparation of reports, use of facilities and expertise, and on science & technology (i.e., HC, DFO, NRCAN, AAFC).
Provincial/ Municipal/ Local Governments	Collaboration on development and delivery of air quality forecasts, standards for monitoring and data exchange, and priorities and logistics for field studies i.e., Pacific 2001, Toronto Niagara Region Study.
National Research Council (NRC)	Collaboration on priority setting, management and definition of projects, preparation of reports and use of facilities and expertise – i.e. Environmental Research Aircraft Facility (ERAF)
United States and other national governments	Collaboration on development of research strategies, coordination of intensive field studies, monitoring protocols, data quality management and data exchange standards, and environmental assessments *i.e., NARSTO -North American- Particulate Matter Assessment for Canada, United States and Mexico.* Includes participation on intergovernmental panels such as the IPCC, IAI, IJC, US WRP, WWRP, and WMO.
Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)	Collaboration on priority setting, project review, and implementation of research plans carried out primarily by universities.

Application of new knowledge to deliver on program priorities and initiatives is another area where collaboration is essential. Most new knowledge is gained in order to improve policy, and service. The following diagram illustrates the general flow of knowledge gained from ACSD research, into improved policies and services for Canadians and the international community.

Knowledge Sharing



ACSD	Atmospheric and Climate Science Directorate
OGDs	Other Government Departments
EPS	Environmental Protection Service of Environment Canada
ECS	Environmental Conservation Service of Environment Canada
CMC	Canadian Meteorological Service

Major Accomplishments

This section summarizes significant accomplishments within the ACSD R&D programs over the five-year period from 1996-2002.

This report is structured by organizational branches for convenience, although many research issues and disciplines, like the atmosphere itself, are cross-cutting and are not influenced by artificial boundaries.

Climate Research Branch (CRB)

CRB conducts process research, participates in field programs, performs data analysis, and develops and runs numerical models – all with the focus on climate and climate change science.

Introduction

There is ongoing collaboration between CRB and the other organizational units of ACSD. Examples include collaboration with the Air Quality Research Branch (AQRB) on water and carbon cycle research, and with the Meteorological Research Branch (MRB), on seasonal forecasting. CRB also provides R&D support for operational activities within MSC. This support takes the form of advice and guidance, i.e. improvement of precipitation measurement techniques with the Atmospheric Monitoring and Water Survey Directorate (AMWSD), and collaborative development work in seasonal forecasting with the Atmospheric Environmental Prediction Directorate (AEPD).

A major success of CRB has been the strong and productive research collaboration that has been developed with the Canadian academic community. This interaction takes the form of direct scientist-to-scientist collaboration, as well as more formal program arrangements such as the Climate Research Network (CRN) and Canadian Cryosphere Program. These partnerships have allowed CRB scientists to provide leadership and to be effective participants in the national climate research agenda. This has helped to build a strong climate science capacity in Canada, – resulting in **Canada's effective international participation in programs like the World Climate Research Program (WCRP) and the Intergovenmental Panel on Climate Change (IPCC).** CRB scientists have made strong contributions over the years to international climate research programs, primarily the WCRP. Many of the Branch's research activities are essential or closely linked to WCRP projects.

The activities of the Climate Research Branch fall into three inter-related program areas:

- Climate Modelling and Analysis;
- Climate Processes and Earth Observation; and
- Climate Monitoring and Data Interpretation.

The Branch is organized into three Divisions (CCCma, CCRP and CCRM), each with a primary responsibility for one of the program areas. In addition, CRB has provided support to the Canadian university community, primarily for climate modelling R&D, through the Climate Research Network (CRN). Accomplishments within each of these areas are described in the following sections.

Climate Modelling and Analysis (CCCma)

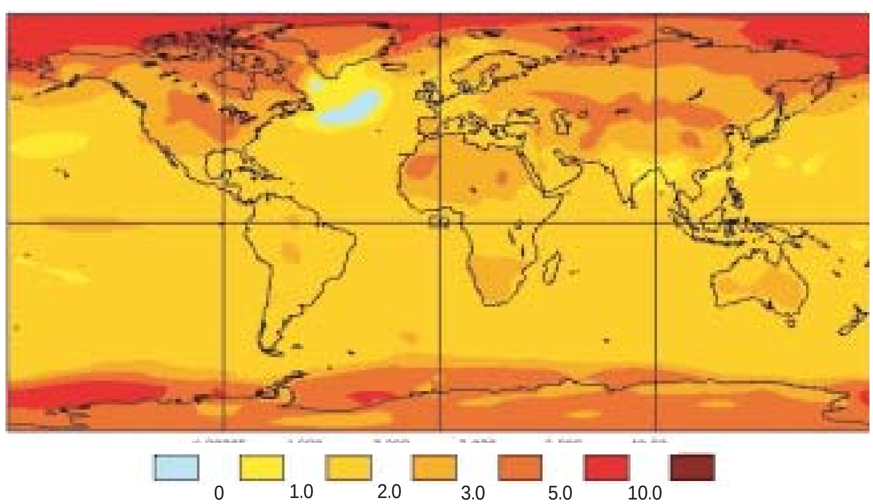
CCCma develops and uses sophisticated atmospheric and coupled climate models and advanced analyses of observed data and model output to improve understanding of present, past and future climates.

Models and analysis tools are used in short term climate forecasting, in studies of climate predictability and variability, and to project and analyse the change in climate that will result from human-induced changes in the composition of the atmosphere.

The Division was formed in 1993 when the Climate Modelling and Analysis Division of the former Canadian Climate Centre was moved to the campus of the University of Victoria. This was done to enable better access to ocean and sea-ice modelling expertise located on Canada's West Coast. CCCma immediately undertook the development of its first coupled model, CGCM1, which became operational in 1996.

This model consists of the well-tested AGCM2 atmospheric model (T32L10), a version of the GFDL MOM ocean model (1.875 degrees, L29), a one-layer land surface scheme, and a thermodynamic sea-ice scheme. A substantial number of simulations have been performed with CGCM1 including a 1000-year control run, a 250-year transient greenhouse gas only run, an ensemble of three 250-year greenhouse gas plus aerosol runs using the IS92a forcing scenario, a 1000-year stabilization run using the year 2050 forcing from the IS92a scenario, and a similar 1000-year run using year 2100 forcing. Papers describing the model, its reproduction of the 20th century climate, and projections for the future were published in the year 2000. Several papers describing other analyses of the model output have also been published.

Surface warming projected by CGCM2 - 2050 vs 1980



An improved version of the model, CGCM2, became operational in 1998. This model has the same configuration as CGCM1 but it incorporates the Gent-McWilliams ocean mixing parameterization and the Flato-Hibler dynamical sea-ice model. This model has also been run extensively, including a 1000-year control simulation and three ensembles of three runs using the IS92a, A2 and B2 forcing scenarios, respectively. A paper describing the difference in the forced response with CGCM1 has been published, as have analyses of some other aspects of these simulations. Active analysis of both CGCM1 and CGCM2 output continues.

A third version (CGCM3) became operational in a research mode in 2001. The new model features CCCma's new atmospheric model (AGCM3; described below), a version of the US National Center of Atmospheric Research's (NCAR) CSM Ocean Model (NCOM1.3) adapted for CGCM3, a sophisticated multi-layer land surface package (CLASS 2.7; developed in CCRP), several dynamical sea-ice options, a river routing scheme, a land-ice discharge scheme, and a 'message passing interface' based coupler that controls the simultaneous operation of the various model components. All three versions of the GCM model are flux adjusted, but with adjustment substantially decreasing in magnitude and frequency with each model version. Research leading to a non-flux adjusted model is underway.

CCCma has also developed improved atmospheric models incorporating new parameterizations, developed both at CCCma and elsewhere. AGCM3, which was frozen in 1999, is configured to operate at T47 and T63 horizontal resolutions and typically has 32 levels in the vertical. The model includes such improvements as an 'optimal' spectral topography that minimizes Gibbs ripples over oceans and provides sharper surface gradients in mountainous areas, an anisotropic gravity wave drag parameterization, improved boundary layer and cloud parameterizations, a new parameterization of deep convection and radiation code improvements. AGCM3 is now operating in the development version of the CCCma coupled model (CGCM3) and is being deployed for seasonal forecasting at the Canadian Meteorological Centre. An AMIP2 simulation performed with the model has been transferred to the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for evaluation.

There has been rapid progress on the development of a further improved atmospheric model (AGCM4; still in testing) which includes: prognostic cloud water; a bulk sulphur cycle that is linked to the cloud microphysics; a new parameterization of shallow convection; an innovative implementation of the correlated-K radiative transfer scheme that is both fast and accurate; and a new parameterization of cloud inhomogeneity effects.

CCCma contributed substantially to the IPCC Third Assessment Report (TAR). Two of the four Canadian lead authors participating in Working Group 1 come from the Division. **CGCM1 and CGCM2 are amongst the few models that have been run sufficiently to be used in the IPCC climate change and detection assessments that are the basis of the strong IPCC statement on the effect of anthropogenic emissions.** CCCma is also one of only a small number of groups that were able to produce projections of future change using the IPCC A2 and B2 emissions scenarios in time for the TAR.

CCCma models are also used for other assessments. Equilibrium change simulations performed with AGCM2, coupled to a mixed layer ocean, were used in the Canada Country Study (see Adaptation and Impacts Research Group). CGCM1 was one of two main models used in the US National Assessment of the Impacts of Climate Variability and Change (the other being HadCM2). CGCM2 will be used in the Arctic Climate Impact Assessment (ACIA).

Dissemination of model output for the use of others has been performed via the IPCC Data Distribution Centre, which has recently accepted the CGCM2 A2 and B2 simulations, via CCCma's own website, and via the Canadian Institute for Climate Studies (CICS) Climate Change Scenarios group. **The CCCma website makes more than 2800 years of climate model output available to users via a user friendly web interface.** The selection of data offered includes a broad range of variables and some daily data as well as monthly mean data. Users have downloaded over 14,000 datasets since the inception of the website in 1998, with more than 8,000 downloads since January 2000.

Seasonal forecasting is another important application of CCCma models. CMC produces operational seasonal forecasts using an ensemble forecasting system based on AGCM2 and the recherche en prévision numérique (RPN) SEF model. This system is the result of collaboration involving CCCma, RPN, the Canadian Meteorological Centre (CMC) and McGill University. Ongoing R&D in this area is now focused on deploying new CCCma and RPN models (AGCM3 and GEM) for seasonal forecasting.

The Division puts considerable emphasis on analysis of observed and simulated climate and includes the following:

- Intra-seasonal to inter-annual predictability and decadal predictability;
- Observed and projected changes in cyclone frequency, the variability of simulated annular modes, and how it might change in future climates;
- Projected changes in extremes; and
- Simulated hydrological cycles and projected changes in streamflow.

CCCma has also contributed significantly to WCRP model intercomparison projects such as CMIP (Coupled Model Intercomparison Project), AMIP (Atmospheric Model Intercomparison Project), SMIP (Seasonal Model Intercomparison Project) and SIMIP (Sea-Ice Model Intercomparison Project), and to the literature on analysis methods.

The emphasis on analysis includes the continual development and improvement of the CCCma diagnostic package. This "package", which is closely integrated with the modelling environment, provides users with a powerful scripting language for the analysis of observed and simulated climate data. CCCma, and many others, use it both as a research tool and for the operational post-processing of model output.

CCCma has been effective in mobilizing talent for modelling and analysis via collaborations. Researchers across the country have been engaged on topics such as:

- Climate variability and predictability (Derome, McGill);
- Development and application of a regional climate model (Laprise, UQAM);
- Development of a middle atmosphere model (MAM) with a full stratospheric chemistry package (Shepherd, University of Toronto; McConnell, York);
- Development and implementation of aerosol parameterizations (Lohmann, Dalhousie); and
- Development and implementation of improved sea ice modules (Weaver, University of Victoria).

Recently, CCCma has entered into a collaborative agreement with the Institute of Ocean Sciences (IOS) and the Department of Fisheries and Oceans (DFO) that has allowed a senior DFO research scientist to move to CCCma. **This additional expertise in modelling the ocean carbon cycle will help accelerate efforts to develop a coupled model that includes a carbon cycle.** This innovative collaboration builds on carbon cycle work that has already been done at CCCma (i.e. it has implemented an inorganic C-cycle in its ocean model).

A great deal of effort is put into transferring technology developed through collaboration into CCCma models. For example, several sea-ice treatments are now available in CGCM3, and the gas-phase and heterogeneous chemistry packages developed for the MAM are being integrated into the AGCM. Technology is also transferred to others, including the deep and shallow convection schemes, the anisotropic gravity wave drag scheme, the AGCM3 physics package (which has been installed in the regional climate model), AGCM3 itself (for use as the basis of the Middle Atmosphere Model, paleo-climate research at the University of Toronto, and seasonal forecasting at CMC), and the diagnostics package.

CCCma has been successful in mentoring and training highly qualified personnel. Several 'graduates' of the group have gone on to develop their own research careers. CCCma also retains some of the best of its postdoctoral fellows as research scientists. Members of the Division are also active in graduate student supervision, the supervision of co-op students, and the mentoring of stagiaires from European schools.

Overall, CCCma is an effective research unit that despite its modest size has attained considerable success both nationally and internationally. This can be attributed to the unified approach that it has taken in the development of its models and analysis of modelling results, and to its effective engagement of expertise in the university sector.

Climate Processes and Earth Observation (CCRP)

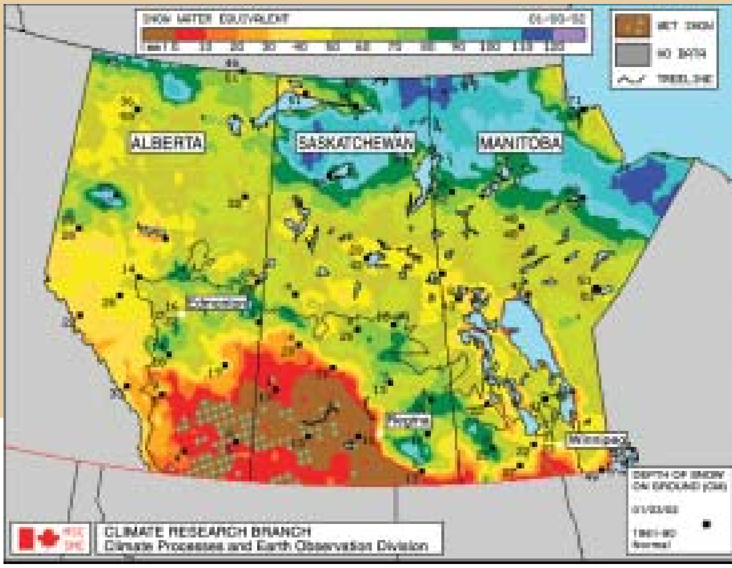
This program conducts research to improve the understanding of energy, water and carbon cycles, with an emphasis on cold climate processes. This involves understanding of the role of the cryosphere in the climate system, and the development and implementation of improved remote sensing and field measurements.

The Division places special emphasis on the measurement and modelling of land-surface processes, and on the evaluation and application of regional climate and weather models as integration tools. Most of the activities in the Division also contribute to the scientific basis for a strengthened water program in Canada.

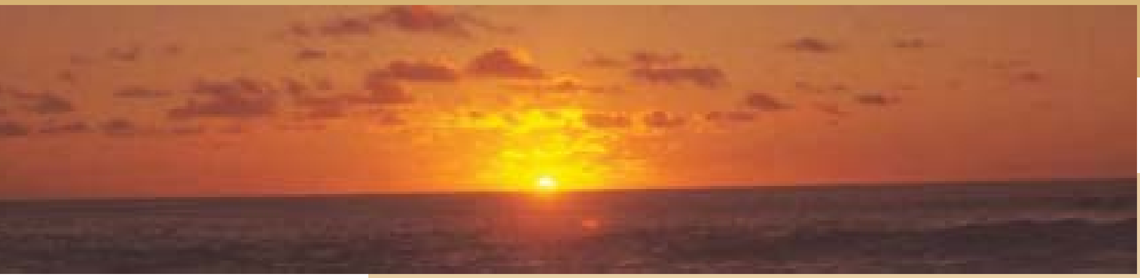
CCRP scientists have been active participants and leaders in the major Canadian contribution to the Global Energy and Water Cycle Experiment (GEWEX) – the Mackenzie GEWEX Study (MAGS). Their work has led to new insights into the processes and feedbacks occurring within this high latitude region. Key findings from the first phase of MAGS include:

- Quantification of moisture recycling over the basin - showing that close to half of the warm season precipitation over the region is derived from local evapotranspiration.
- Characterization of the feedback between precipitation processes and environmental conditions affecting the precipitation efficiency of high latitude, cold season precipitation systems.
- Identifying the importance of synoptic-scale disturbances on the development of extreme winter warming events over the basin.

The Canadian Regional Climate Model (CRCM) was a key tool in the MAGS to study the interannual variability of different hydrological components over the basin. A special issue of *Atmosphere-Ocean* in 2002 is devoted to the results from the first phase of MAGS. The second phase of MAGS (2000-2005) places high priority on the transferability of acquired knowledge and models to other river basins, and to a global observing period which links all component basins.



Satellite derived snow water equivalent (SWE) over the Canadian Prairie Provinces for March 1, 2002. The lack of snow cover in southern Alberta and southwestern Saskatchewan is a significant feature on the map, which contributed to the drought conditions that affected this area during the 2002 summer.



The interactions between the atmosphere and its underlying surfaces need to be more realistically included in climate models. The land-surface processes activity is a combination of field and model studies aimed at better understanding exchanges and flows of energy, water and greenhouse gases, and improving their representation in climate models. Field investigations by CCRP scientists and university collaborators at the Boreal Ecosystem Research and Monitoring Sites (BERMS) have provided new insights into land surface processes. Some key findings include:

- the profound effect of land cover type and the patchy mosaic character of the boreal landscape on forest evapotranspiration;
- the effect of interannual climatic variability on carbon and water exchange from the boreal deciduous forest – showing spring temperature to be the critical climatic control on carbon and water exchange;
- the relative timing of when BERMS boreal conifer and deciduous ecosystems act as carbon sources or sinks; and
- the timing of spring thaw may be the most critical determinant of net ecosystem productivity in the boreal region, with the link to changes in the cryosphere in this region being of direct relevance.

The modelling component of this activity is the Canadian Land Surface Scheme (CLASS) – a world leading land surface process model that is coupled to the CCCma's, GCMs, and the CRCM. Two new versions of CLASS were developed over the last five years. They incorporate new features such as variable soil depths, a more efficient surface temperature iteration scheme, a new mosaic structure, improved evaporation and evapotranspiration algorithms, a new organic soil parameterization, improved near-surface turbulent transfer functions, re-worked snow property algorithms, and full coupling to the Canadian hydrological routing model, WATFLOOD. The evaporation and turbulent transfer improvements were introduced in response to the findings of past Project for Intercomparison of Landsurface Parameterization Schemes (PILPS) experiments. These and the other updates drew on the results of testing against field datasets obtained through the Climate Research Network land surface node.

Scaling is an important aspect in both field and modelling studies. At BERMS, a multi-scale approach, including eddy covariance and chamber methods, has been used to improve the understanding and description of the biophysical processes and estimates of the annual carbon balance. In modelling with CLASS, a series of scaling experiments has been performed using the CRCM for the 1995 melt period (April-June), by varying the resolutions of either the model or input surface fields (from 15 km –150 km). Effects of smaller scale processes and/or subgrid variability of surface conditions on the model snowcover and its melting were investigated through intercomparison of the results from these different simulations.

In order to address important socio-economic issues related to climate change in Canada, policy and decision-makers need a better understanding of the cryosphere and its role in the climate system. Division scientists have led in the development and evolution of the Canadian collaborative project, the Cryosphere System in Canada (CRYSYS), which has provided improved measurement, monitoring, and modelling over a range of spatial and temporal scales.

On a hemispheric scale, Division scientists have conducted a detailed assessment of historical in-situ and recent satellite observations, and documented a significant long-term decrease in spring snow cover over Eurasia, and a trend toward increasing winter snow accumulation over North America. Passive microwave data have been used to investigate the interactions between regional patterns of snow water equivalent (SWE) and atmospheric circulation.

A collaborative investigation to document the response of the cryosphere to the extreme warming over the Canadian Arctic, in the summer of 1998, has found that the variable response was linked to three broad process categories:

- Preconditioning;
- Critical events; and
- The role of local-scale differences in the physical environment.

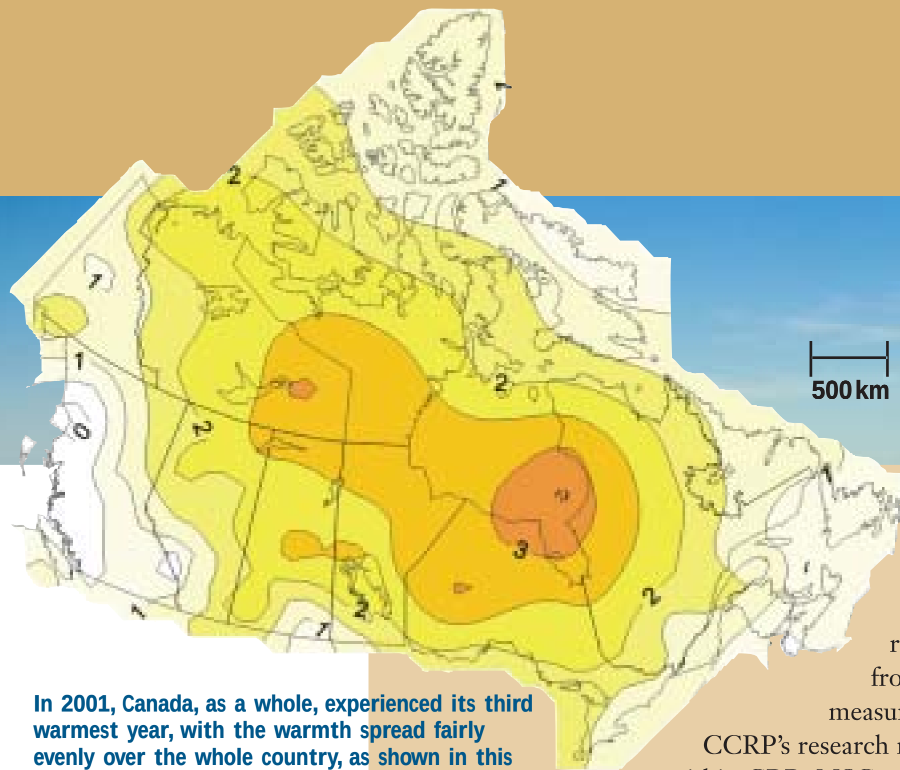
These areas of research will become increasingly important as the Climate and Cryosphere project (CliC) of the World Climate Research Program (WCRP) develops, and as related Canadian Space Agency programs are funded.

For Canada, given its sparse conventional networks, remote sensing is becoming increasingly important for systematic observations of the climate system. The application of available satellite information and the development of new methods for interpreting atmospheric conditions (e.g., from the CloudSat mission) and surface conditions (e.g., cryosphere and soil state) are critical. Using novel visualization methodologies, CCRP scientists were the first to use SSM/I 85.5GHz data to derive large-scale sea ice motions over the Arctic Basin.

The Division's research has advanced the use of remote sensing for snow water equivalent (SWE) determination from passive microwave for climate and hydrology to include its real-time use. Others agencies have used and tested CCRP's SWE algorithms (e.g. the National Snow and Ice Data Center (NSIDC) has used the CCRP prairie SWE algorithm to generate near real-time global snow and sea ice extent products for EOS instrument teams). New algorithms for SWE retrieval from passive microwave satellite data were developed, tested and implemented operationally for the boreal forest region in western Canada allowing for a 'seamless' representation of SWE in the Prairie Provinces.

Field and airborne experimentation have been key components in developing these new techniques. CCRP has developed a unique high and low frequency airborne microwave radiometer installation on the National Research Council's (NRC) Twin Otter in support of CCRP climate/cryosphere research (via MSC/NRC Aircraft Facility), allowing targeted experimentation over a range of environmental conditions. Collaboration with water resource managers has provided opportunities to develop much needed operational products, while providing CCRP with testing and validation of its algorithms and procedures.

The science of measurements is the basis upon which climate and meteorological observations are made. An important contribution in this activity was the successful completion of the World Meteorological Organization (WMO) Solid Precipitation Measurement Intercomparison Study that was led by CCRP scientists. This study yielded important findings about snow measurements around the world. Its results have been widely accepted and they have improved the understanding of precipitation gauge characteristics and its measurement physics. These procedures provide the basis for more accurate precipitation fields for water balance and model validation studies, the development of improved precipitation datasets for climatic trend analyses, and the development of criteria for evaluating and certifying new precipitation gauges for the MSC network. This research is particularly valuable in view of the trend toward automation.



In 2001, Canada, as a whole, experienced its third warmest year, with the warmth spread fairly evenly over the whole country, as shown in this annual temperature anomaly map.

In summary, CCRP activities are focused on improving understanding of energy, water and carbon cycles in the climate system. Within the Division, research activities are vertically integrated from in- situ and remotely sensed measurements, to process studies and modelling. CCRP's research results support other research programs within CRB, MSC and EC, and have contributed to national and international programs. CCRP scientists have led major international studies and their research results have gained international recognition.

Climate Monitoring and Data Interpretation (CCRM)

CCRM monitors and analyses the Canadian and global climate in order to document and understand climate trends and variations, including changes in extremes, and to attribute these changes to global warming, changes in the circulation of the global atmosphere and ocean, or other causes. This involves the acquisition, adjustment and analysis of instrumental and proxy data for the Canadian landmass and surrounding marine areas.

The Division has devoted considerable effort and resources over the past five years to developing and analysing high quality, homogenized, climate datasets. CCRM has developed a methodology for removing inhomogeneities from temperature and precipitation records, and has applied this approach to produce a new database of carefully adjusted monthly-mean temperature and precipitation records for climate change studies in Canada. A procedure to adjust daily temperatures has also been developed and implemented, and the sensitivity of perceived trends in extremes to the adjustments has been investigated. The Division continues to update these datasets. The adjusted precipitation dataset has recently been increased from 60 to 495 Canadian stations.

CCRM also works on other aspects of instrumental data. For many applications it is highly desirable to have gridded rather than station data. CCRM has produced gridded monthly datasets for mean temperature and precipitation anomalies. These data are used for a variety of purposes, including the verification of seasonal hindcasts and the monitoring of current climate. The introduction of automated stations in Canada poses additional challenges for monitoring and detecting climate change. CCRM has assessed the effects of the introduction of autostations at several sites where there have been co-located manned and automated stations. Work is now underway to develop suitable adjustment methods so that long-term climate records can be extended into the future.

There is also potential to extend instrumental records back in time, particularly in the St. Lawrence Valley (Lower Canada) where there are meticulous records of temperature, precipitation, and surface pressure that extend back as early as 1750. A pilot study indicates that it is feasible to digitize and interpret these data.

Significant progress has also been achieved toward the homogenization of historical marine wind observations – accounting for differences in observing platform, method of observation, and flow distortion. The Division is also involved in the assessment of new marine observational technologies from ships and buoys. This work has been done in close collaboration with the Comprehensive Ocean-Atmosphere Data Set (COADS). In addition, the Division has collaborated with the Southampton Oceanography Centre to calibrate wind measurements from several research vessels, and in the use of dynamical modelling to generalize the flow distortion characteristics of classes of merchant vessels.

CCRM data products are disseminated to users in a number of ways. A subset of the homogenized data is integrated into the datasets that are regularly forwarded to WMO to meet Canada's international commitments. **Homogenized monthly mean temperatures and precipitation datasets are made available to the scientific community via the CCRM website.** This recently introduced service has generated great interest and has stimulated communication with climate researchers outside the Division.

The homogenized datasets are also included in the Global Climate Datasets that are distributed by the Climatic Research Unit (University of East Anglia, UK). Daily and gridded data are made available on request. The Division has provided scientific and technical advice on the use of the homogenized datasets and on climate trends and variability to several organizations including the regional offices of the MSC, the CMC, and CICS (Canadian Institute for Climate Studies). It has also collaborated in several projects for the comparison of homogenization and trend analysis techniques with the Monitoring Services Division (Burlington), Institut National de Recherche Scientifique (Quebec) and National Climatic Data Center (Asheville, US). The Division provides input for the design and implementation of the Canadian Global Climate Observing System (GCOS) stations to the National Climate and Weather Networks Branch.

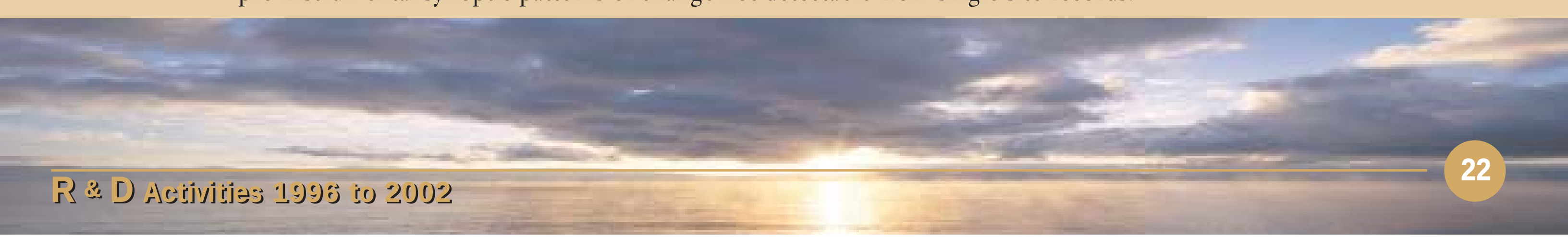
The Division provides useful regional and national, seasonal and annual, service to Canadians through the Internet-based *Climate Trends and Variations Bulletin* (CTVB) through historic data rehabilitation and timely monitoring of current conditions across Canada from synoptic stations. Authoritative information of the type contained in the bulletin help to provide proper perspective for events such as 1998 – the warmest year on record in Canada.

CCRM has used its carefully adjusted datasets to identify climate trends and changes in extreme events over Canada. Temperature in southern Canada has increased significantly over the century, with the greatest warming in the daily minimum values when compared to daily maximum. Precipitation has also increased during the last century, but there is no evidence to suggest changes in the intensity of extreme daily events. For the past half century, the country shows significant warming in western Canada, accompanied by a cooling in the Northeast. Precipitation has increased significantly over the Arctic region, while the ratio of snowfall to total precipitation has decreased over southwestern Canada.

The trends in climatic variables are consistent with those observed in several hydroclimatic variables for Canadian streams, including trends in streamflow and river ice. In southern Canada, where temperature has increased significantly and precipitation has changed little, annual streamflow has decreased significantly. Work is progressing on analysing extremes of multi-day precipitation accumulation and on seasonal and annual precipitation climate indicators over Canada. The Division has recently began to study formal detection of climate change at regional scales in collaboration with CCCma, making use of both the data resources in CCRM and the climate change simulations produced by CCCma.

Climate Indicators from Proxy Data

A complementary area of activity is the reconstruction of climate indicators from proxy data. This work has proceeded with the collaboration of a number of paleo-data researchers. Since 1997, the Division has worked to develop a tree ring network that coincides with the gridded historical climate network to yield new information on pre-instrumental synoptic patterns of change not detectable from single site records.



Studies of tree-ring width chronologies sampled across a broad network in the southern Cordillera, Northern B.C. and the Yukon showed tree-ring chronologies suitable for the reconstruction of long time series precipitation-related parameters. Variation within these chronologies shows a close association with Pacific North American (PNA) and Pacific Decadal Oscillation (PDO) forcing mechanisms. In another project, the Division's homogenized instrumental record has been combined with Prairie tree ring records to produce Palmer Drought Severity Index (PDSI) series at several locations that extend back more than 400 years. Preinstrumental climate information has also been derived using temperature data from over 140 boreholes in Canada. This has allowed for the construction of maps of critical climate periods during the past several centuries, demonstrating, for example, cooling events (18th and 19th centuries) and warming events (16th-17th centuries, and 20th centuries).

Once change is detected in the climate system, the next step is to understand its causes (i.e., attribution). Recent successes in this area include **establishing the impact of El Niño-Southern Oscillation (ENSO) on Canadian temperatures and precipitation, establishing its effects on the probability of extremes of temperature and precipitation, and on the occurrence of tornadoes in Canada.** Other achievements include finding coherence between ENSO and the North Atlantic Oscillation (NAO) on various time scales, and documenting the combined effects of ENSO, the NAO and the PDO on Canadian climate. CCRM has also investigated the study of the NAO variability on interannual and inter-decadal time scales. Variability and shifts in the NAO have been used to explain the cooling trend in eastern Canada during the second half of the 20th century.

In collaboration with scientists at the National Oceanic and Atmospheric Administration (NOAA), a statistical Canonical Correlation Analysis (CCA) seasonal prediction scheme was developed in 1996 for Canadian temperatures and precipitation in collaboration with scientists at NOAA. This has since been transferred to CMC for the production of 1, 2 and 3 season lead seasonal forecasts. These long-lead forecasts, along with their skill levels, are made available on the Internet. The Division's gridded datasets are used at CMC in the validation of seasonal hindcasts produced with the CCA method, and with CMC's dynamical forecasting system.

CCRM also investigates variability and change in the marine environment (winds and waves) as part of the federal Program of Energy Research and Development (PERD). Achievements in the past three years include the world's first global 40-year wind and wave reanalysis, based on the National Center for Environmental Prediction (NCEP)-NCAR reanalysis. In addition, a detailed, high-resolution, 43-year continuous wind and wave hindcast of the North Atlantic Ocean has just been completed, incorporating detailed tropical storm reconnaissance, re-assimilation of all wind observations – accounting for measurement height and type, and manual kinematic analysis of all storms during the complete period. Several analyses of trend and variability have been published on both the global and North Atlantic wave reanalysis that relates the variation in the spatial patterns, particularly for extremes, to variations in the global circulation regimes, including the NAO, and to variations in storm tracks. The homogeneity of the reanalysis datasets has also been investigated. A statistical downscaling of wave heights for the North Atlantic to the year 2100, based on surface pressure relationships using the CCCma coupled climate model, has recently been completed. Extensions are in progress using the ECHAM4, HADCM2 and HADCM3 models.

In summary, CCRM is able to contribute significantly to global climate data resources and to the understanding of climate trends and variations. Several Division members have participated in the Intergovernmental Panel on Climate Change's Third Assessment Report (IPCC TAR) as contributing authors and several serve on national and international bodies.

The Climate Research Network (CRN) and the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)

One of the major accomplishments of the Climate Research Branch has been the creation of the Climate Research Network (CRN). Initiated in 1994, this network has been very successful in engaging the energies, ideas and talents of the university community to expand and complement the scientific knowledge and expertise available in the country with respect to climate change and climate variability.

In recent years, the network has consisted of nine collaborative research groups, each focusing on a specific area of climate research, primarily in support of climate model improvement. Several significant advances have been made in climate modelling through the CRN:

- Development of a middle atmosphere model that is now integrated with the CCCma AGCM;
- Development of a regional climate model that is being used along with the CGCM to provide regional scale climate change scenarios;
- Development of a comprehensive land-surface process scheme that has been incorporated into climate models in Canada and abroad; and
- Advances in understanding of climate variability and predictability.

With the creation, in 2001, of the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), MSC decided to phase out support for the CRN with the expectation that support to the network would continue from the new foundation. It has been satisfying to see that the CFCAS has continued funding some nodes and started up new ones in key areas of climate science (e.g., cloud modelling and terrestrial carbon cycle modelling). CRB researchers are active participants in all of these networks.

Air Quality Research Branch (AQRB)

AQRB conducts R&D in areas of systematic measurements, numerical modelling, processes research, and extensive field studies – all focused on air quality issues. The Branch's atmospheric chemistry research focuses on advancing knowledge of the chemistry of the atmosphere, investigating how it is changing, and understanding how these changes affect the physical behaviour of the atmosphere.

Introduction

The Branch came into existence in the mid-1970's. The first major issue it focused on was acid deposition (acid rain in the public vernacular). The sound science and dedication of AQRB scientists, coupled with effective collaboration within Environment Canada and with provincial counterparts, resulted in a strong case being made for the control of acidifying emissions in northeastern North America.

AQRB also plays a central role in providing the science necessary to deliver air quality products and services to the Canadian public. A good illustration of this is the UV Index program. Canada was the first country in the world to introduce next-day forecasts of UV Index, in 1992. The program was only possible because of the decades of high quality measurements of UV and the associated understanding that AQRB scientists had developed. Close collaboration with the operational arms of the Meteorological Service of Canada enabled an effective transfer of knowledge and technology from research to operations. Since the launch of the UV Index, a variety of air quality forecasts and advisories have been developed and have been well received by Canadians.

The Branch has also provided valuable input to the development of environmental policies and services in Canada by making significant contributions to major science assessments. These include; the NO_x/VOC 1996 Science Assessment, the 1997 Canadian Acid Rain Assessment, the 1997 Canadian Arctic Contaminants Assessment, the 2001 PM Precursors review, and international assessments such as the Arctic Monitoring and Assessment Reports, IPCC assessments and the WMO/UNEP Scientific Assessments of Ozone Depletion. The Branch also produced the widely distributed 1997 book: *Ozone Science: a Canadian Perspective on the Changing Ozone Layer* for the 10th Montreal Protocol Meeting in Montreal.

AQRB research is currently focused on five specific air quality issues; smog, acid deposition, hazardous air pollutants (HAPS), stratospheric ozone and greenhouse gases. Each issue has common R&D components such as; requirements for field studies, ongoing measurements, data analysis, and numerical modelling. Instead of having individual research teams organized by issue, the Branch has four pools of expertise that are combined as necessary, on a project basis, to investigate specific air quality issues. This is reflected in the organizational structure of the Branch, which is comprised of four Divisions:

Systematic Measurements and Data Analysis (ARQM)

- Develops methods for routine monitoring of a wide range of atmospheric constituents and parameters, and
- Develops leading-edge data analysis techniques.

Processes Research and Special Studies (ARQP)

- Leads in the design and implementation of intensive field studies, and
- Develops research-grade measurement methods required to advance the understanding of atmospheric processes.

Modelling and Integration (ARQI)

- Develops air quality models, and ensures the transfer of this technology to operations, and
- Plays a key role in the design and implementation of emissions databases.

Experimental Studies (ARQX)

- Conducts both ground-based and space-based measurements of radiation, and
- Maintains key international radiation measurement standards.

The majority of AQRB staff work at the MSC National Headquarters in Toronto but operate monitoring stations, observatories, laboratories and other facilities across Canada. Approximately 40 monitoring stations are operated in co-operation with Environment Canada regional staff in locations ranging from the Pacific to the Atlantic, and from the Great Lakes to the High Arctic. Several key observatories are operated in collaboration with a wide range of partners including other government departments, universities and the private sector. The Branch also supports numerous global and international initiatives at many of the monitoring sites, and operates and maintains databases and computer models.

Systematic Measurements and Data Analysis Division (ARQM)

AQRM has contributed to scientific understanding on a Canadian and global scale through the long-term, high quality, systematic measurement of key atmospheric constituents, and through the development of new and improved measurement techniques. Integrated into these measurement systems are sophisticated quality assurance/quality control, data archiving and data analysis activities.

The Division's measurement programs are usually directed at understanding the behaviour of targeted pollutants on a national scale. However, ARQM's R&D also addresses issues that may only affect a particular region of Canada, especially those involving transboundary transport. The Division's measurement programs are generally located in non-urban environments, away from the direct influence of urban and industrialized areas.

ARQM also develops and maintains critical databases and software for the collection, quality control, quality assurance, archiving and subsequent analysis of monitoring data from Canada and the United States. These capabilities are applied across the various air quality issues and are referred to below as "cross-cutting capabilities."

Measurement Programs for National Air Quality Issues

CORE Network

MSC's CORE network provides long-term, high-quality observations of atmospheric composition and radiation at locations representative of major airsheds and geographic regions across Canada. In addition to providing key, long-term information across several air quality issues, data from these sites contribute to programs such as the World Meteorological Organization's (WMO) Global Atmosphere Watch (GAW) and the Global Climate Observing System (GCOS).

CORE sites are located in five regions of Canada: Arctic, Pacific Coast, Prairies, Industrialized East (Ontario and Quebec), and Atlantic Coast. All sites carry MSC's commitment to maintain operations over the long term (i.e., the next 20 years or more). Each site provides the critical infrastructure necessary to support a broad range

of air quality measurements as required by Canadian and international research projects. The CORE network provides a valuable platform and test bed for development of measurement and data quality management methods. The CORE Network sites are:

1. Alert/Eureka in the Arctic:

Alert is located on the northern tip of Ellesmere Island, approximately 650 km from the geographic North Pole. The baseline measurement program at Alert is Canada's contribution to WMO's Global Atmosphere Watch network (GAW). Alert is one of only 30 or so sites in the world that carry a "global" designation. This means that the site is located in a pristine area where it is possible to make measurements of the global distribution of atmospheric constituents, without the influence of local sources. Alert is also part of Environment Canada's Ecological Monitoring and Assessment Network (EMAN). The Alert site is twinned with a laboratory at Eureka, part of the Network for the Detection of Stratospheric Change (NDSC), where measurements of the stratospheric ozone hole have been conducted.

2. Saturna on the Pacific Coast:

Saturna Island is the most southern of the Gulf Islands located between Vancouver Island and mainland Canada/US. Measurements at this site include acid deposition and tropospheric and stratospheric ozone. Greenhouse gas measurements are being made at nearby Estevan Point. Saturna is a "regional" site in the GAW. This means that measurements made at the site are representative of an area covering several hundred kilometres. Saturna is part of the Canadian Air and Precipitation Monitoring Network (CAPMoN), the Canadian Sunphotometer Network (AEROCAN) and EMAN.

3. Bratt's Lake on the Prairies:

This WMO Baseline Surface Radiation Network (BSRN) site is located about 30 km south-southwest of Regina. In addition to radiation measurements, measurements are made of mercury, ozone, sulphur dioxide, nitric acid, particulate matter and precipitation chemistry at the site as part of the CAPMoN, AEROCAN, and CAMNet (Canadian Atmospheric Mercury Measurement Network) programs.

4. Egbert, Ontario in the Industrialized East:

This site is located at the Centre for Atmospheric Experiments (CARE), approximately 70 km north of Toronto. CARE provides a platform for acid deposition, toxics, ozone and aerosol measurements. CARE is also a GAW regional station, and an EMAN, CAMNet, AEROCAN and CAPMoN site.

5. St. Anicet, Quebec in the Industrialized East:

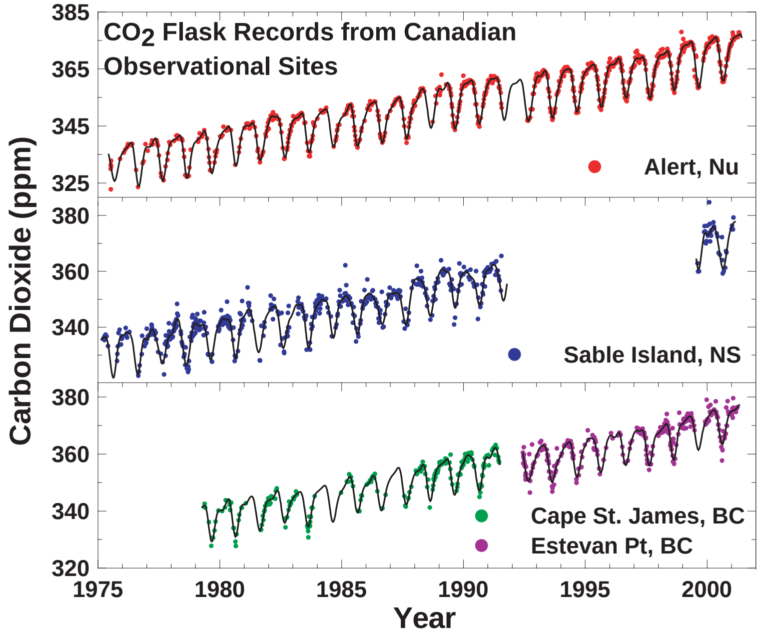
This rural site is located about 40km southwest of Montreal and has been used as a staging area by Environment Canada and university scientists for a broad range of measurements. These include measurements of ozone, oxides of nitrogen, particulate matter, carbon monoxide, peroxyacetylnitrate, atmospheric mercury and pesticides. Flux measurements of carbon dioxide, water vapour, lead and mercury are also made at the site, as are radiation and micrometeorological measurements. St. Anicet is an EMAN and CAMNet site.

6. Kejimkujik on the Atlantic Coast:

This site is located in southern Nova Scotia, about 160 km from Halifax. A long historical record of air and precipitation chemistry, ozone and some toxics and aerosol measurements have been recorded at the site, as well as EMAN activities. Kejimkujik is a GAW regional site as well as being in the CAMNet and CAPMoN programs. The site is twinned with Sable Island, in the Atlantic Ocean some 300 km to the south, where a long historical record of greenhouse gas measurements provides invaluable data that is relevant to climate change.

Climate Change: Greenhouse Gases

ARQM has contributed significantly to scientific understanding of the global carbon cycle through a program of long-term, high precision, systematic measurements of carbon dioxide, methane, nitrous oxide, sulphur hexafluoride, carbon monoxide and chloro-fluorocarbons (CFCs) – the only such program in the country. Scientists and researchers use the Division's carbon measurement data worldwide in their investigations of the global carbon cycle and climate change.



Long-term trends of carbon dioxide concentrations, based on weekly flask measurements at three Canadian Baseline Stations.

These measurements are made at coastal, interior and Arctic locations and constitute part of Canada's contribution to the WMO's Global Atmosphere Watch Program (GAW). Division scientists have analyzed the data and found trends in seasonal and annual variations of atmospheric concentrations of these compounds and **estimated the magnitude of Canadian sources and sinks of greenhouse gases.**

International intercomparison studies have ranked Canada's CO_2 measurements to be at the highest level of accuracy and precision in the world. The measurements are made to a precision of better than 0.02 ppm (parts per million). This level of precision exceeds, by a factor of 5, the target of 0.1 ppm set for the Northern Hemisphere by the WMO. Highly precise measurements are essential to reduce the uncertainty in estimates of global sources and sinks of carbon – an issue of central importance in understanding the global carbon balance. To put this in perspective, a longitudinal drop of merely 0.4 ppm from the west to the east coast of North America would indicate a North American carbon sink equal to half of the global total.

The value of a long-term data set from a location like Alert – the most northerly site in the WMO's GAW – has been proven time and time again. Statistical data analyses and model interpretations of Alert data have shown a much higher level of wintertime biological activity than had previously been thought. This has a significant effect on Arctic CO_2 levels.

Another greenhouse gas, methane, has also been the subject of ongoing measurements and study by ARQM researchers, who have made significant contributions to furthering understanding of the methane cycle and the global methane budget. **Atmospheric methane measurements from northern Canada suggest that global methane fluxes from wetlands at high latitudes in the Northern Hemisphere are overestimated, and that methane fluxes have high interannual variability (related to temperature).** The data suggest that previous assumptions about the significance of climate feedback mechanisms on methane emissions may have been significantly (5 times) underestimated.

The Stable Isotope Research Laboratory has participated in global carbon cycle research since 1997, making stable isotope measurements to locate carbon sources and sinks on a national and global scale. The current status of carbon cycle research shows that global and regional inversion models are unable to predict the strength of sources and sinks (flux) to an acceptable level of accuracy (i.e. < 0.5 Gigatonnes carbon per year). This finding underscores the importance of developing sufficiently accurate carbon and oxygen isotope measurement programs, and further advancing the understanding of regional processes that influence carbon sources and sinks.

ARQM has also focused on improving the accuracy of stable isotope measurements and has developed a method to link daily carbon and oxygen isotope measurements to a primary standard (VPDB). **This method has been demonstrated to be the most accurate and precise in the world for carbonate CO_2 measurements** and will be adopted by the European Commission CARBOEUROPE program, through the collaboration between the AQRB's Stable Isotope Research Lab and the Max-Planck-Institute for Biogeochemistry.

Acid Deposition

The Canadian Air and Precipitation Monitoring Network (CAPMoN) has made measurements of acid deposition and related atmospheric constituents across Canada for over two decades. Measurements from the network have been crucial in defining the 'acid rain' issue. Daily measurements of air and precipitation chemistry are used to characterize air and precipitation quality and to estimate regional-scale wet and dry deposition across the country.

CAPMoN measurements are recognized internationally for their high accuracy, precision and comparability and are used worldwide for trends detection, ecosystem health research, and model evaluation. **CAPMoN data have demonstrated that ambient SO_2 and sulphate concentrations at regional locations in Canada have decreased in concert with decreasing North American SO_2 emissions.** However, the data also show that precipitation acidity from the early 1980s to 1995 has not changed markedly in spite of decreasing SO_2 emissions, largely because of concurrent declining levels of neutralizing base cations in precipitation.

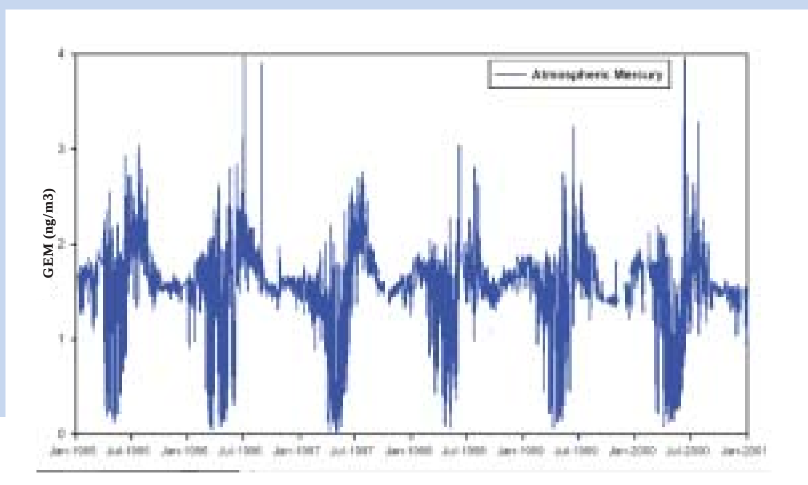
CAPMoN data, analysed collectively with data from other networks, show that there have been striking reductions in wet and dry deposition in certain areas of eastern Canada. Despite this reduction, over 500,000 km^2 of eastern Canada continue to exceed the critical load of sulphate, and therefore remain at risk for aquatic damage. The data also show that although sulphur emissions and deposition have declined, the picture is different with respect to nitrogen species. NO_x emissions over northeastern North America have remained relatively constant over the past twenty years, and this is reflected in nitrate wet deposition patterns, that do not show any significant reduction.

Since its inception, CAPMoN has been committed to ongoing intercomparison studies to establish the comparability of Canadian and US acid deposition data. This effort was rewarded when it was revealed that the collection programs, which yielded essentially comparable results for most species, were not at all comparable for ammonium. This has serious implications for the use of combined Canadian/US wet deposition data in spatial analyses and nutrient budget studies. The cause of the ammonium discrepancy appears to be biological conversion/uptake of ammonium in the weekly samples collected in the US network.

Mercury

The Canadian Atmospheric Mercury Measurement Network [CAMNet] was established in 1997 to measure the spatial and temporal variation of mercury in air and precipitation across Canada. The network consists of 13 stations across Canada that provide spatial coverage from Newfoundland to British Columbia, and from Ontario to Nunavut.

Although CAMNet has only been operating for a relatively short period of time, the network has already determined that mercury concentrations tend to be fairly uniform across rural Canada. However, this background level varies dramatically during episodes of elevated or depleted mercury concentrations. Further research is underway to understand the variability of



Gaseous atmospheric mercury concentrations measured at Alert, Nunavut from 1995 to 2001. Note: From March 12 to May 17, 2001 the Hg data was inter-polated from ozone measurements made at that time.**

mercury evident at the CAMNet sites. The network will also provide valuable information on the impacts of future regulatory measures being considered, particularly by the US.

Measurement Programs for Regional Air Quality Issues

Aerosols and Pesticides in the Arctic

Since 1980, weekly filter samples of atmospheric aerosols have been collected at Alert to measure the long-term trend and seasonal variations of major aerosol components, including sulphate, sea salt, black carbon and trace metals. A long historical record of research-grade observations have been collected at Alert that have contributed significantly to the scientific understanding of long-term trends and anthropogenic and natural sources of aerosols.

In spite of its remote location, its polar geography and climatology make Alert a recipient of pollutants not just from North America but also from all of the Northern Hemisphere, including Europe and Asia. The arctic aerosol data have been used in numerous international and national pollution assessments and model validation exercises. This research program has established that predominantly sulphate aerosols that can be attributed to Eurasian SO_2 sources cause wintertime arctic haze. In the 1990s, the program documented a marked decrease in aerosol concentrations – coincident with the industrial collapse in the new Eurasian republics. The measurements also confirmed the effectiveness of a reduction in lead additives in automobile fuels in Western Europe that brought about a major decline (70%) in atmospheric lead concentrations.

Since 1991, Arctic measurements of atmospheric levels and trends of pesticides, commercial products and combustion products have demonstrated how significant long-range transport is to the presence of these substances in the Arctic. A link has been established between changes in global usage of pesticides (in particular Hexachlorocyclohexane-HCH) and air concentrations in the Canadian Arctic. These findings, under the Northern Contaminants Program (NCP), have contributed to the scientific substantiation of the UN ECE protocol on **persistent organic pollutants** (POP's) and the global POP's convention [Stockholm Convention].

Hazardous Air Pollutants in the Great Lakes Basin

Operating the US/Canadian Integrated Atmospheric Deposition Network (IADN), over the past 10 years, has provided insight into the levels and trends of current-use and banned pesticides in air and precipitation that have been deposited into the Great Lakes.

The Canadian portion of IADN consists of two master stations, Point Petre and Burnt Island, and eleven satellite stations situated on or near the shores of the Great Lakes. The purpose of the network is to determine atmospheric loadings and trends of priority toxic chemicals that affect the Great Lakes Basin. These toxics are measured in air and precipitation following protocols that ensure comparability of Canadian and US data.

IADN data have shown that levels of chemicals that are banned or have a restricted use are declining in some cases. **In fact, for some banned chemicals, such as polychlorinated biphenyls (PCBs) past deposition into the lakes is reversing so that the net contaminant flow is now from the lakes to the atmosphere.** Most instances of high air concentrations of banned chemicals in the Great Lakes region can be linked to airflows from previously contaminated regions. However, new and emerging chemicals of concern, such as current-use pesticides, and 'old' chemicals, such as **polycyclic aromatic hydrocarbons (PAHs), are being detected in the atmosphere over the Great Lakes without decreasing trends.**

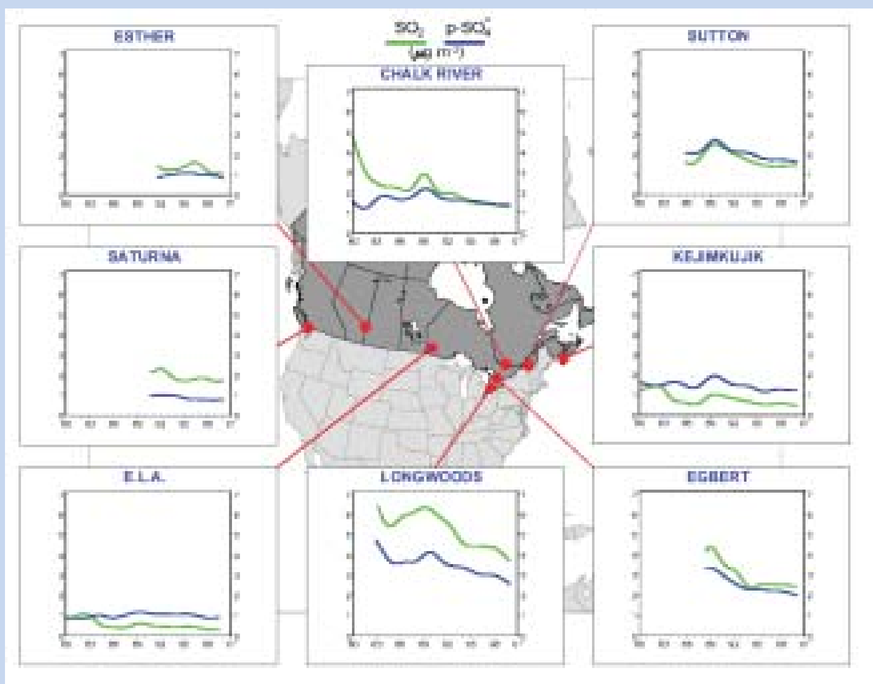
Cross-cutting Capabilities: Development of Database Management Approaches

NAtChem

ARQM developed the National Atmospheric Chemistry (NAtChem) Database and Analysis Facility out of the need for a sound database, state-of-science quality assurance and quality control, and the need for powerful data analysis capabilities. This facility archives and analyses precipitation chemistry, particulate matter, and toxic chemical data, together with its metadata, from major networks in North America.

One of the biggest challenges facing researchers who want to analyse data from different networks is ensuring that data from different sources are actually comparable and can be analysed as one dataset. The inherent differences in measurement protocols and data management standards must be identified and tracked along with each piece of data. NAtChem was successful in establishing a database structure and data management protocol for acid deposition data that has since been generalized and adopted by numerous atmospheric measurement programs.

The powerful capability of being able to treat multiple datasets as one, and to perform sophisticated analyses have been trademarks of the NAtChem facility. **ARQM scientists were able to use NAtChem to demonstrate that transboundary transport of sulphate and nitrate from the US into Canada is significant.** From 1980 to 1996, eastern Canada emitted 13% of eastern US/Canadian SO_2 emissions, but received 41% of the combined US and Canadian sulphate wet deposition. For nitrate, eastern Canadian sources emitted 8% of the combined Canada/US NO_x emissions but received 46% of the US/Canadian nitrate wet deposition. The imbalance between the emission and deposition values is attributed to the transport of sulphur from the US into Canada.



Long-term trends of SO_2 and $SO_4^{=}$ concentrations at rural/remote CAPMoN sites. The $SO_4^{=}$ concentrations at Saturna Island and Kejiimkujiik have been corrected to eliminate sea salt $SO_4^{=}$.

NAtChem has taken the whole process of data exchange one step further. In order to strengthen and streamline the exchange of data between networks, the group developed a new Data Exchange Standard (DES). This data standard, originally known as the NAtChem Data Exchange Standard, has received external recognition and has been adopted by NARSTO, (US/Canada/Mexico research program) and by the WMO's World Data Centre for Aerosols. The scientific community has acknowledged the DES as a major breakthrough in preserving the value of atmospheric data for long-term usage.

Each year, over 100 requests are met by NAtChem staff, ranging from fulfilling simple data requests to the provision of continental-scale maps and datasets for model evaluation exercises, and ecosystem and human health studies. **The NAtChem Database is recognized worldwide as a major source of precipitation chemistry, particulate matter (PM) and toxics datasets – one that integrates large amounts of Canadian and US data, and provides data in a consistent format** employing a state-of-the-art data exchange standard. Recognizing NAtChem's capabilities, the US Environmental Protection Agency is planning to provide funds to the NAtChem Facility to convert it into a combined Canadian-US facility.

RDMQ™

> **ARQM has developed a quality assurance and data management software system that has received worldwide attention. The system, known as RDMQ™ (Research Data Management and Quality Control Software System), provides a formal objective system for quality controlling and managing environmental datasets.**

RDMQ™ is used extensively within AQRB for managing and quality controlling all types of atmospheric chemistry data and has significantly improved the quality, efficiency and timeliness of data analysis activities. It has been licensed to the consulting industry, the WMO's World Data Centre for Precipitation Chemistry, the United States EPA, and the Environmental Protection Service of Environment Canada.

Processes Research (ARQP)

ARQP scientists study the processes that govern how chemicals enter, move through, and exit the atmosphere. The Division's goal is to further the understanding of transformation processes of pollutants and their precursors, and ambient concentrations and deposition of a broad suite of chemicals in air and in precipitation.

Most of the Division's processes research is undertaken on a project basis, with projects lasting of the order of five years. This allows the branch to regularly re-balance its efforts to take advantage of new developments and priorities. Another significant aspect of the Division's work is organizing and participating in large-scale field studies.

Acid Deposition

> **ARQP has conducted several biogenic sulphur studies on the coasts and in the boreal regions of Canada to investigate and evaluate the source strengths of dimethyl sulphide (DMS), which is a biogenic precursor to sulphate aerosols in the atmosphere.**

These studies enabled Division scientists to evaluate the relative importance of biogenic sulphur to anthropogenic sulphur source strengths across Canada. The influences of the Pacific Ocean on the climate and the sulphur source on the West Coast were determined to be of the same magnitude as the anthropogenic sulphur source strength. On the East Coast, the Gulf of St. Lawrence contributes about 13% biogenic sulphur to the total sulphur budget. **With decreasing anthropogenic sulphur source strengths across North America, the biogenic sulphur contribution to the atmosphere, especially in the coastal regions, is increasing in importance.**

Smog

> **Process studies have focused on the issues of emissions, transport, transformation, loss through wet and dry deposition, and re-emissions in some instances, and how these issues impact on the resulting atmospheric concentrations. Studies of the exchange between air and soil, and water and vegetation have been crucial to understanding the fate of certain chemicals.**

The Division's Stable Isotopes Laboratory has demonstrated that stable carbon isotope measurement in atmospheric VOCs (volatile organic carbons) can provide valuable information. **These measurements have advanced the understanding of emission sources and atmospheric processes of VOCs, including transport and chemical removal.** This is possible because stable isotope ratios change during biogeochemical processes, but they do not change as a result of natural decay. This research began in 1998, through collaboration with York University. The group has been the first to develop a method to link on-line (via GC-C-IRMS) carbon isotope measurements to a primary standard (VPDB). Systematic measurements of the carbon isotope composition of individual compounds of non-methane VOCs in air have been carried out at Alert, as have measurements of the kinetic isotope fractionation factors for VOC (non-methane hydrocarbon) reactions with OH- radicals, which is one of the most important removal processes for atmospheric VOCs. The results will be used to interpret the variation of carbon isotopes in VOCs. This will provide key information about transformation processes and for source apportionment.

ARQP scientists have developed accurate, high-sensitivity methods for measuring smog constituents such as peroxyacetylnitrate (PAN), formaldehyde, VOCs and oxygenated VOCs. These methods are used primarily in intensive field campaigns, but the Division has also collected some unique, long-term datasets, including the only long-term PAN dataset in the world.

Hazardous Air Pollutants

While there are innumerable hazardous chemicals in our atmosphere, ARQP toxics research focuses on pesticides, mercury, polycyclic aromatic hydrocarbons (PAHs), polychlorinated napthalenes (PCNS), polychlorinated biphenyls (PCBs), and particulate matter (PM), due to their toxicity, persistence, potential for long-range transport and environmental significance.

An important Division activity has been the development of techniques to sample and analyze atmospheric mercury. Application of these methods has resulted in considerable progress in understanding the environmental cycling and transformation of mercury, during transport. **The discovery of "mercury depletion events" during the 'Polar Sunrise' experiments at Alert, together with elevated snowpack concentrations of mercury, have resulted in a re-examination of our understanding of the atmospheric behaviour of elemental gaseous mercury.**

ARQP has developed and is employing a method to analyze proportions of stereo isomers in toxics that are present in ambient air and in potential source regions. This approach has been used to track levels of chlordane (a pesticide now banned in Canada and the U.S.) in the air over the Great Lakes region to a previous use as a termiticide in the American mid-west. A similar type of analysis for hexachlorocyclohexanes (HCH) has revealed much about the processes of deposition and circulation in the Arctic Ocean and the Great Lakes.

Over the past 10 years the Division has developed the capability to use LIDAR (Light Detection and Ranging) to measure the dispersion and transport of particles, whether in the form of spray or as a result of the transformation of precursor gases into particles. The initial application was to map the dispersion of pesticides from aerial spraying. Subsequent development has allowed the LIDAR to be used for both ground-based and airborne sensing of aerosols during major field studies. LIDAR has proven to be a powerful tool for tracking the transport and distribution of atmospheric aerosols.

Considerable effort has been invested in understanding the spatial and temporal variation in the concentrations of particulate matter. Emphasis has been given to describing both the physical and chemical nature of particles. This information, together with knowledge of the incidence of various health endpoints such as hospital admissions, have resulted in a much **better understanding of the linkages between air pollution levels and health effects.**

Particulate Matter and Health Impacts

The Branch has contributed to a wide variety of research examining the toxic effects of particulate matter to human health.

ARQP research has contributed to the tri-national NARSTO assessment on particulate matter (to be released late in 2002) and to health and atmospheric assessments completed to support Canada-Wide Standards for PM and O_3 *(National Ambient Air Quality Objectives for Particulate Matter: Science Assessment Document)*. It has also played a critical role in the Sulphur-in-Gasoline standards *(Atmospheric Science Expert Panel Report - a Joint Industry/Government Study on Sulphur in Gasoline and Diesel Fuels)*.

For over ten years, ARQP has collaborated with the air quality health effects research section of Health Canada. The intent of this collaboration has been to provide ongoing support related to air pollutant exposure with an aim to being an integral part of their research, from the planning stages to completion. This has led to considerable technology transfer between the two research groups, and research findings with significant impact/policy relevance.

Most recently, we have initiated human clinical studies at the University of Toronto that have uncovered new evidence of the cardiovascular effects of PM and/or O_3. This research is now being expanded through new significant funding from the US EPA via a new collaboration with the University of Michigan. AQRB has contributed to a wide variety of research examining the toxic effects of particulate matter in laboratory studies, personal exposure assessment to particulate and gaseous air pollutants, ambient characterization studies for prospective health studies and risk characterization and development of multi-pollutant time series for epidemiological studies. The outcomes of this collaboration have been integral parts of federal government assessments (e.g., 1997 Acid Rain Assessment) and the development of Canadian air quality policies (CWS for PM and O_3, sulphur in fuel regulations). The research has been widely recognized internationally, including support to the U.S. regulatory process (e.g., PM Criteria Documents).

Other Processes Studies

ARQP has also contributed to understanding of the indirect effect of aerosols on climate.

MSC measurements have been used as the basis for an empirical parameterization that relates cloud droplet number concentrations to aerosol sulphate mass. This parameterization has been used in a number of climate models to estimate the indirect radiative forcing of climate by aerosols.

Intensive Field Studies

One of the most effective ways to make significant progress in the understanding of air quality-related atmospheric processes is to mount intensive field studies. These studies are designed to measure the broadest possible suite of atmospheric constituents at times and locations that are carefully selected to provide information about transport and transformation on a range of spatial and temporal scales.

These campaigns involve leading-edge technology and state-of-science understanding of the issues being studied – and they are usually dependent on Mother Nature to provide suitable meteorological conditions. Because of the effort and resources required to conduct significant field studies, they are usually planned years in advance and carefully coordinated to allow participation of as many researchers as possible. One of the biggest benefits to be derived from participation in these campaigns is the leverage of knowledge that occurs. **Our scientists are able to collaborate and share data with a wide circle of experts and gain access to databases and expertise that would normally not be available to them.**

Some of the significant findings from field studies that the Division has participated in over the past six years are listed below:

NARSTO/CE (ATLANTIC96)

Measurements of particle size distributions and biogenic hydrocarbons in this field study provided the first mechanistic link between biogenic hydrocarbons and particle development in a natural environment.

Polar Sunrise

The remoteness of the Alert observatory has made it an ideal location to study tropospheric chemistry in the Arctic. At this location, **AQRB scientists discovered the phenomenon of ozone depletion in the Arctic boundary layer during polar sunrise.** The importance of this discovery can be gauged by the remarkable 282 times that their paper, published in *Nature*, has been cited since its appearance in 1988. This finding has also led to at least two additional key discoveries.

Mechanistic considerations led to the prediction that the ozone depletion is driven predominantly by a B_rO_x cycle. Branch scientists undertook measurements of the BrO molecule and verified that this process was indeed occurring. This led to a much wider study of BrO, and its presence in the atmosphere has now been

The ice camp at Alert, Nunavut, during a 2002 Polar Sunrise Study focussed on mercury processes.

confirmed at many locations in the world. **This discovery has filled an important void in the understanding of tropospheric ozone chemistry.**

Another important discovery that came originally from studies into tropospheric ozone depletion mechanisms, was that the snow-pack in the Arctic is a very reactive medium. The snow-pack stimulates the photochemically-driven production of compounds that lead to HO_x molecules in the boundary layer (e.g. formaldehyde to HO_2; nitrous acid to HO).

Northern Wetlands

This field study combined intensive surface and aircraft measurement campaigns of CO_2 and its isotopes, and modelling exercises over the Hudson's Bay Lowlands. Results demonstrated that a biospheric flux signal of CO_2 is transported from the boundary layer to the free troposphere in a sporadic, convective process. This is different from the gradual process parameterized in inverse models that estimate biospheric fluxes from atmospheric CO_2 measurements. **The study showed that the footprint for atmospheric CO_2 over a continental site is a function of both the source/sink distribution and of the topography.**

Forest Fire Studies

A dynamic emissions model was developed to estimate the emissions from Canadian forest fires, and is currently being incorporated into the Regional Climate Model (RCM). In the short term, this work will be used to estimate the contribution from boreal forest fires to the particulate matter (PM) burden - and its implications for Canada-Wide Standards for PM. It will also be used to estimate visibility reductions over remote and populated regions of Canada, including the Arctic. In the longer term, this work will assist with the development of a forest fire emissions model for use in Environment Canada's large-scale air quality and climate models.

Pacific 93

The Air Quality Research Branch launched the Pacific 93 oxidant study in 1993 to focus on oxidant transformation and distribution in the Lower Fraser Valley, BC. This was the first extensive study of oxidants in the area. Most of the measurement results have been published in a special issue in *Atmospheric Environment*. The study clearly demonstrated the interaction between complex meteorology and chemistry in the region. In particular, the nocturnal variation of the flow pattern (up-valley and down-valley pollution movement) was well documented. Superimposed on this meteorological pattern were the complex chemical reactions that lead to the formation of ozone. Biogenic emissions were demonstrated to have a significant impact on the oxidants. Emission measurements inside a tunnel were used to reduce the uncertainties in the emissions inventories for mobile sources. New remote sensing technologies were used to map out the flow patterns and spatial distribution of pollutants in the valley, and the vertical structure of the pollution distribution.

Pacific 2001

The Air Quality Research Branch conducted the Pacific 2001 air quality study in British Columbia to provide modellers and policy makers with further scientific understanding of PM and ozone formation in the Lower Fraser Valley. Field measurements were conducted at 5 main ground sites and at a number of ancillary sites. The emissions from automotive, biogenic, and agricultural sources were characterized as to the chemical and physical properties of particulate matter produced, and the transformation and transport processes that were occurring. Airborne measurements mapped out the pollution distribution and flow patterns in the valley. Particulate matter in the valley has now been well characterized chemically in terms of inorganic and organic species. Significant amounts of organic carbon account for 30-60% of the mass, with sulphate and nitrate aerosols contributing to the rest. A significant alteration of sea salt aerosols was found to occur in urban pollution – chloride was replacing nitrate, a process that depends on the extent of the interaction between sea salt and urban pollution.

Modelling and Integration Division (ARQI)

ARQI develops air quality models to represent chemical and physical processes in the atmosphere. These models are used to support policy development by evaluating potential emissions scenarios, or for service delivery through the production of air quality forecasts and advisories.

Modelling the atmosphere is a complex task. Air Quality Research Branch works in close collaboration with the Meteorological Research Branch to provide air quality-specific modelling expertise, and with the Pollution Data Branch of EPS (Environmental Protection Service) who provides them with emissions information.

The main priority of the Division in recent years has been to replace earlier "issue-specific" models with a one-atmosphere, multi-pollutant model designed to address multiple air quality issues. The task is challenging but the rewards are significant. A unified air quality model will better represent the complexity of the real atmosphere and the interactions between pollutants. In addition to developing air quality models, ARQI plays a key role in the design and implementation of emissions databases.

Acid Deposition

The Branch designed a regional-scale system to prepare emission information in a format that can be easily input into air quality models.

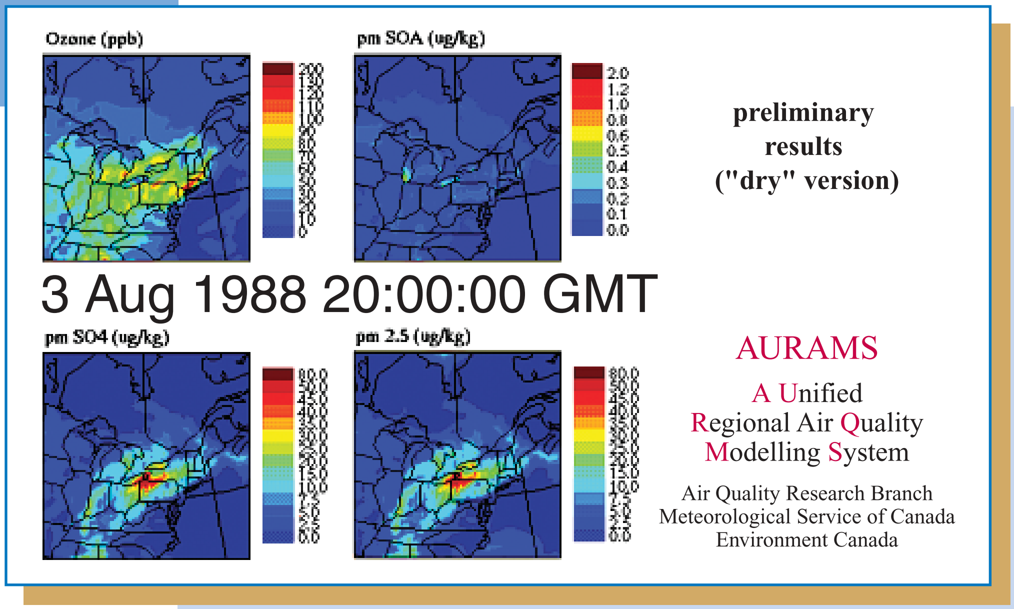
Whenever model runs are to be conducted, one of the most labour-intensive tasks is taking relevant emissions information and converting it into a format and structure that can be used by the models. ARQI scientists made significant progress in this area when, in 1997, they put together the Canadian Emissions Processing System (CEPS) – a regional-scale system designed specifically to prepare emissions files for use by the Division's air quality models. CEPS was later used in conjunction with the numerous air quality models (e.g., ADOM, ALSM, AURAMS, and CHRONOS). The resulting processed emissions files have been utilized by several external organizations. **CEPS has improved the quality of Canadian emissions inventories by identifying areas that needed improvement, and were subsequently improved.**

When the Acid Rain Working Group of the Canadian Council of Ministers of the Environment (CCME) met to draft a post-2000 Canadian national acid rain strategy, they used outputs from ARQI's Acid Deposition and Oxidant Model (ADOM) to guide them. The model was run with several future year SO_2 emissions scenarios. The model outputs established that SO_2 emissions in Canada and the US must be reduced a further 50 to 75% from currently legislated limits in order to meet critical loads in eastern Canada. **This finding has been the basis for negotiating the next set of federal/provincial and Canada/US emission reductions.**

Smog (Ozone and Particulate Matter)

The Division's Canadian Hemispheric and Regional Ozone and NOx System (CHRONOS) – a chemical transport model for air quality research and application – has been used for emission control scenario runs as well as for air quality forecasting.

The Environmental Protection Service of Environment Canada, in bilateral negotiations on the Canada-U.S. Air Quality Accord, used outputs from CHRONOS. The model is the primary tool for providing quantitative guidance for air quality forecasting across Canada. Since 1998, the Division has given priority to development of a unified air quality model. The new model is AURAMS – A Unified Regional Air Quality Modelling System – a size-resolved, chemically characterized, episodic PM and ozone modelling system being developed in Canada for multi-pollutant air quality research. Modelling advances in AURAMS include vectorization of the gas-phase, aqueous-phase and heterogeneous



chemistry mechanisms, and a new gas-phase dry deposition scheme. **AURAMS will provide policy makers with a next-generation scientific tool for evaluating the non-linear impacts of concurrent multiple-pollutant emission changes.** This is a significant step forward in representing a more holistic view of the atmosphere and how it may react in response to complex and inter-related changes in emissions.

The Division made a major contribution to the particulate matter (PM) precursors review that took place in 2001. **The PM precursors review was a primary document in support of the Canadian government's declaration of PM as toxic under the Canadian Environmental Protection Act (CEPA).** Support for the review included the preparation and analysis of unified North American emissions fields and the first systematic comparison over North America of the relative contributions of major conversion pathways between atmospheric VOCs and organic aerosols. A new and detailed VOC lumping scheme, suitable for both ozone and PM modelling, was used for the latter effort.

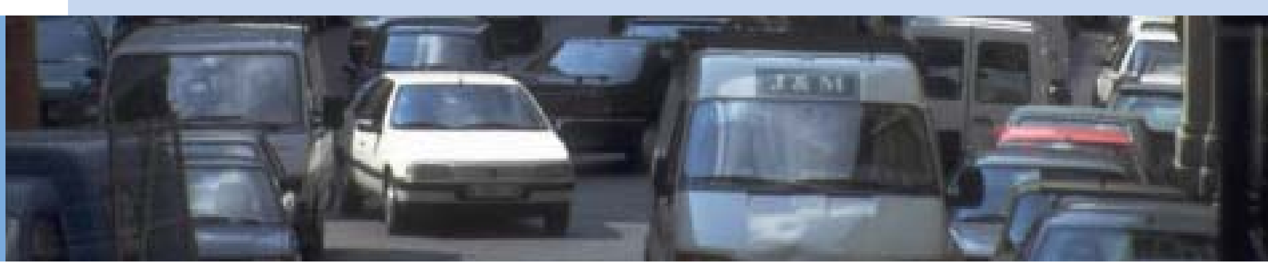
ARQI has also improved the modelling of dry deposition of pollutants to the earth's surface and the modelling of interactions between the atmosphere and forest canopies. The canopy model was used to determine fluxes of biogenic VOCs and interactions between micrometeorology and chemistry. The model showed that emissions estimates of biogenic VOCs might be underestimated by 30% if the chemical losses within the canopy are not taken into consideration.

Hazardous Air Pollutants (HAPs)

ARQI has prepared an excellent world population dataset that is used by various organizations, worldwide. The dataset was implemented, along with improved global inventories of various pesticides, to support global modelling of HAPS.

Analysis of the inventories revealed a link between global usage of pesticides (in particular HCH) and their air concentrations in the Canadian Arctic. This was the impetus for the global Multi-compartment Environmental Diagnosis and Assessment (MEDIA) model for simulating environmental transport of persistent organic pollutants that was applied to examine the global distribution of HCH.

In a complementary effort, the Global and Regional Atmospheric Heavy Metals (GRAHM) model for the transport and transformation of mercury (a long life heavy metal which is highly toxic and hence of high concern) was conceived. At this point, some preliminary evaluations and mercury budget estimates by



continent have been completed. These two global models, MEDIA and GRAHM, may be combined in the future into a single, larger framework if it is appropriate.

On the regional scale, a higher resolution regional air pollution model has been used to compute deposition of heavy metals to the Great Lakes. **The model results have been used in Canada/U.S. agreements on Great Lakes water quality.**

Development of NARCM (Northern Aerosol Regional Climate Model) began in 1996 under the Canadian Climate Research Network (CCRN) initiative to study the impacts of atmospheric aerosols on climate. A key component of the project was the Canadian Aerosol Module (CAM), which is a size-segregated aerosol algorithm to treat the emission, clear sky dynamics, dry/wet depositions and aerosol-cloud interactions. In spring 2001, NARCM was successfully applied to simulate the soil dust emissions in China during the ACE-Asia (Aerosol Characterization Experiment) period and their subsequent transport across the Pacific Ocean into North America.

Other Modelling-related Research

In addition to the development of air quality models in support of policy and service, the Division has been active in carrying out several innovative research projects that have been published in the peer-reviewed literature and have potential for application in future models.

A short list includes:

- Investigation of numerical methods for the solution of stochastic coalescence equation, describing the time evolution of an aerosol spectrum and the development of the high resolution model for the simulation of the Junge Layer, a layer of sulphate aerosols in the stratosphere;
- Pioneering application of semi-Lagrangian non-oscillatory methods for the solution of the fluid equations in Businesq and anelastic approximation for the study of convection in geophysical fluids;
- Theoretical studies of the role of chaotic advection for the mixing of chemical tracers in geophysical systems. This may have important implications for how pollutants are mixed and their availability to undergo chemical reactions in the atmosphere;
- Evaluation of the radiative forcings of the atmosphere following a major volcanic eruption using the global spectral model and the bulk sulphate aerosol scheme;
- Application of satellite data for the evaluation of the Sundqvist scheme used to predict cloud water content in numerical weather prediction models; and
- Investigation of numerical methods for the solution of the convection-diffusion equation in porous media. The results were used in the development of the soil module for the toxics transport model MEDIA.

TransCom3 (2000-2001)

This project involved 16 atmospheric CO_2 transport-modelling groups from various nations. ARQP participated using the global dynamical model (SEF) developed at RPN (see MRB). The results, to be published in *Nature*, show the range of uncertainties in atmospheric transport models that calculate global and regional distributions of carbon sources and sinks. This international effort identifies crucial improvements required to reduce uncertainties in CO_2 transport model predictions.

Experimental Studies Division (ARQX)

The Experimental Studies Division is the research lead for the ozone depletion issue. The Division's focus is primarily on stratospheric ozone-related atmospheric chemistry and radiation measurements and process studies. The majority of ARQX activities have been in systematic measurements, metrology, field process studies (particularly from balloons and aircraft), trend analysis, and space measurement studies.

The Division is committed to studying the relation between ground and space-based measurements, with the aim of improving understanding of both approaches. This improved understanding may lead to even better measurement systems that would incorporate the benefits of both ground and space-based measurements. These studies include modelling the transfer of radiation, including polarization.

Much has been learned about the issue of ozone depletion over the past decade. One of the remaining challenges, however, is developing and maintaining a highly precise and accurate measurement capability – one that uses multiple methods to reliably detect and validate global changes of the order of 1%. This is an area where ARQX has made significant contributions in the past and can continue to contribute into the future.

The improvements in both ground and space-based measurement methods, such as better intensity, and higher spectral, spatial and temporal resolutions, are now showing potential for application to measurement of tropospheric constituents. Combined with improved inversion and data assimilation techniques, these measurement methods may improve significantly our capability to model and predict vertical distributions of several atmospheric constituents.

The Canadian Middle Atmosphere Model (CMAM) [described under MRB] is the national focus for chemical dynamic modelling of the stratosphere. ARQX is contributing to CMAM data assimilation, specifically by working on the development of 3D-var assimilation for stratospheric ozone data.

Brewer Ozone Spectrophotometer

ARQX developed the Brewer instrument for measuring column ozone and UV-B and subsequently licensed it to the private sector for production. The Brewer instrument has become the standard for ground-based measurements and is used in 41 countries around the world. The Division maintains the Brewer calibration centre and its reference triad, which comprises three Brewer instruments that function independently at the same location in Toronto. Analysis of their data (since 1984) provides critical information on the measurement stability of Brewers, and therefore of Brewer measurements around the world.

ARQX is committed to the highest level of quality control and quality assurance of its measurement programs, and has played a key role in investigating discrepancies between TOMS (Total Ozone Mapping Spectrometer) satellite, and Brewer and Dobson ground-based measurements. The Division conducted the ground-based measurements for the NASA TOMS 3F campaign in Alaska in March 2001 and has published a paper explaining some of the discrepancies between the three methods.

The operation of Brewer instruments in Toronto allowed Canada, in 1993, to be the first in the world to detect the increase in monthly and seasonal UV-B radiation due to stratospheric ozone depletion.

Canadian Ozonesonde Network

The Canadian ozonesonde network consists of five to six stations that launch routine weekly flights of ozonesondes, a practice that was initiated at Resolute Bay, Nunavut in 1967. Resolute has the world's longest continuous ozonesonde record; flights from four other stations started only a few years later. The network has produced a valuable long-term dataset, allowing for the determination of long-term trends of height-resolved ozone concentrations at any level of the atmosphere.

ARQX flew ozonesondes in the European-led MATCH (Model for Atmospheric Chemistry and Transport) in 1991-2001 campaigns. **The data obtained from these coordinated flights in both North America and Europe have provided definitive proof of the existence of, and the most thorough characterization of, ozone destruction in the springtime Arctic stratosphere.** Analysis of 30 years of arctic ozonesonde data has revealed an increasing trend in the occurrence of the low altitude ozone destruction episodes of the type studied during the AQRB's Polar Sunrise campaigns. This arctic tropospheric trend has been linked to changes in arctic ice cover, possibly caused by global warming. Outside the Arctic, tropospheric ozone decreased by a few percent per decade up to about 1993; it has subsequently increased so that today the average values are similar to those of the early 1980's.

Observatories

ARQX is responsible for two key observatories, the Network for Detection of Stratospheric Change (NDSC) site at Eureka, and the Baseline Surface Radiation Network (BSRN) site at Bratt's Lake, Saskatchewan.

The importance of Eureka has been recognized in many studies. **Measurements from Eureka have been credited with characterizing the 1997 Arctic ozone depletion event, which illustrates the potential delaying of ozone recovery due to increasing greenhouse gases.** The observatory was mothballed in June 2002 due to funding shortages. Some of the measurement activities have since been moved to the Eureka weather station. Options for alternative funding and management are being explored. The Bratt's Lake observatory has attracted numerous Canadian and international measurement programs. The station is part of the MSC's CORE network for systematic measurements, selected to represent the atmospheric regime over the Canadian Prairies. It is the only Canadian station in the World Climate Programme's Baseline Surface Radiation Network.

Balloon and Space-based Measurements

In 1998, 2000 and again in 2002, stratospheric large-payload balloon flights were conducted as part of the Middle Atmosphere Nitrogen Trend Assessment (MANTRA) project. The project was undertaken with the Canadian Space Agency (CSA), several universities, and industry. A series of papers have been submitted for a special issue of the journal, *Atmosphere-Ocean*, based on the findings of these studies.

SCISAT-1, Canada's first science satellite in 30 years is scheduled for launch in March 2003. The payload is the Atmospheric Chemistry Experiment (ACE), which includes MAESTRO – an instrument capable of measuring stratospheric and tropospheric ozone, aerosols and other trace species. MAESTRO is based on a series of small spectrometers flown by ARQX during the past ten years on balloons and high-altitude aircraft. The acronym indicates **M**easurement of **A**erosol **E**xtinction in the **S**tratosphere and **T**roposphere by **R**etrieval from **O**ccultation. ARQX, CSA (Canadian Space Agency), universities and industry collaboratively developed the instrument.

WMO World Ozone and UV Radiation Data Centre

ARQX has operated the WMO World Ozone and UV Radiation Data Centre (WOUDC) since 1992. The WOUDC and the ARQX web sites have been developed to allow easy access to ozone and ultra-violet (UV) data that is of public interest.

Examples of ozone and UV data include forecast maps, near-real time measurements from the Canadian networks, same day maps of ozone derived from global ground-based measurements, and composite ozone data from ground and satellites. Although the WOUDC is primarily for the use of scientists, most of the archived data are easily available in interesting graphical forms suitable for non-specialists.

UV Index Program

In 1992, Canada became the first country in the world to implement a UV Index program.

The core of the program is the UV Index – a simple measure of the sunburning effectiveness of the radiation (the highest observed terrestrial value is 16; a typical strong summer value in Canada is 8). The program was made possible by close collaboration between ARQX, MRB and CMC scientists. Other factors important to the success of the program included the availability of near-real time ozone measurements from the Brewer network and confidence in the knowledge of the relation between ozone, forecast meteorological variables (pressure, temperature, etc.), and the dependence of UV on ozone and other variables. ARQX and the Science Assessment and Integration Branch (SAIB) have worked together to launch Environment Canada's UV Index Sun Awareness Program and the Sun Savvy School Club to provide resource material to teachers and students on sun protection. The program is widely accepted in Canada and has proven to be useful as a vehicle to help deliver other health-based information and advice to the public. The index definition has been adopted by WMO/WHO and similar organizations and is now operating in many countries.

Science Assessments

AQRX has made valuable input to the development of environmental policies and services in Canada by making significant contributions to major science assessments.

Major science assessments include:

- Ozone Science: a Canadian Perspective on the Changing Ozone Layer, Environment Canada, CARD 97-3, 119 pages, 1997, editors Wardle, Kerr, McElroy, Francis: Contributors, Fioletov & Tarasick, Shepherd, McConnell & Chartrand, Fioletov & Evans, Gallagher, Morrison, Percy & Cameron, Vaughan & Pauli, Cullen, Alward & Kamal [c. 5000 copies distributed].
- Arctic Ozone: The sensitivity of the ozone layer to chemical depletion and climate change, Environment Canada, EN56-133/1998E, 28 pages, 1998, Fergusson and Wardle [written for the non-technical reader, c. 8000 copies distributed].
- ARQB scientists, as well as being contributing authors in key international assessments, were lead authors of:
    - The aerosol chapter in the 2001 IPCC Third Assessment Report;
    - The UV chapter in the 1999 IPCC Aviation and the Global Atmosphere Assessment; and
    - The UV chapter in the 2002 WMO/UNEP Scientific Assessment of Ozone Depletion.

Meteorological Research Branch (MRB)

MRB conducts R&D on severe weather, numerical weather and environmental prediction, data assimilation, satellite meteorology, radar meteorology and cloud physics – with the goal of improving weather and environmental predictions and warnings in Canada.

Introduction

MRB's work covers a wide range of activities from process research to method development that is carried out in a highly collaborative manner, both within ACSD and in a broader circle of collaborators. MRB collaborates with the Climate Research Branch (CRB) on seasonal forecasts. It collaborates with the Air Quality Research Branch (AQRB) on development of air quality forecast methods for specific pollutants such as ground level ozone, and on modelling and forecasting stratospheric ozone and UV radiation. Numerical Weather Prediction (NWP) R & D (both modelling and data assimilation) is performed in close partnership with the Canadian Meteorological Centre (CMC). Both partners work together throughout the entire development process of projects to ensure the smooth transfer of technology into operations. MRB collaborates with CMC, Environment Canada regional science units, and EC regional weather centres on a continuing basis, to improve the underlying science and to develop appropriate methods to transfer science in support of Canada's operational weather prediction and warning program.

In 1999, MRB launched a new program, the Canadian Weather Research Program (CWRP) – a partnership between government, universities and the private sector to promote research initiatives on weather forecasting – to reduce impacts from severe weather, with a priority on high latitude meteorology and precipitation. CWRP has strong ties to the United States Weather Research Program and the World Weather Research Program (WWRP). These ties will accelerate the development of new methods and more efficient means to forecast weather, and reduce the impacts of extreme weather on Canadians. The launch of the Canadian Foundation for Climate and Atmospheric Science (CFCAS) has allowed universities to obtain funding for projects in CWRP priority areas to work in collaboration with MSC scientists. Several million dollars of funding has been granted in areas related to heavy precipitation analysis and prediction, behaviour of tropical cyclones in the middle latitudes, and severe summer and winter storms in the Great Lakes.

A new initiative, the Laboratoire universitaire sur le temps extreme (LUTE) was launched in 2001 in Montreal. This new initiative, together with the existing operational prediction infrastructure, will produce research in priority areas within CWRP. LUTE will also provide professional development to operational meteorologists that will complement the partnership in training and development, initiated by MRB in 2001, with the United States National Weather Service Cooperative Operational Meteorological Training Program (COMET).

MRB is organized into the following three Divisions:

- Numerical Prediction Research;
- Data Assimilation and Satellite Meteorology; and
- Cloud Physics Research.

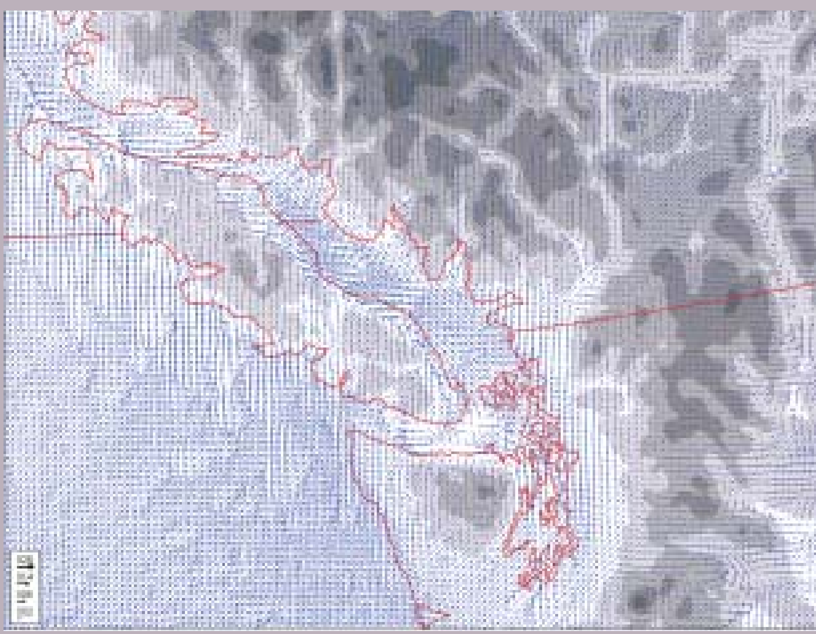
Accomplishments and priorities for each of the Divisions are described in the following sections.

Numerical Prediction Research (RPN)

The Numerical Prediction Research Division (RPN) develops and implements an environmental forecasting and post-processing system based on the Global Environmental Multi-scale (GEM) model. The recent International Peer Review Panel declared the GEM model a world leader.

A growing number of meteorological and environmental prediction (EP) applications within the MSC are now either based on, or directly use, the GEM model. The GEM model is currently used operationally with the global data assimilation cycle to produce medium-range meteorological forecasts. A different configuration of the same GEM model is used operationally in regional data assimilation to produce high-resolution short-range forecasts, and the GEM model is used for urban scale prediction.

Environmental prediction provides linkages between land, ocean and atmosphere (and its chemistry). The science behind environmental prediction plays a role in helping us understand and respond to environmental, economic, social, and political issues. The GEM model is interfaced with a variety of environmental models, like hydrology, chemistry and wind energy prospecting models.



The community model MC2 run over Vancouver Island at 2km horizontal resolution: 17H forecast valid 26 June 1997 2000 UTC. Near surface flow (arrow with scale in knots in lower left corner) superimposed over topography (gray shades every 500m). Only one arrow for every other grid point is displayed for each direction.

There is a growing demand to quantify the non-deterministic aspect of weather and environmental prediction at all time and space scales by means of ensembles to improve the usefulness of the forecast, i.e. to produce probabilistic forecasts for operational decision systems for economical, agricultural and industrial management. The GEM model is now part of the medium-range ensemble prediction system at the MSC.

During the years 1996-2001, the benefits of several years of R&D were realized with the transfer of the GEM model to operations. This first occurred in February 1997, in a regional configuration and then in October 1998, in a global configuration. GEM was added to the medium-range ensemble prediction system in August 1999.

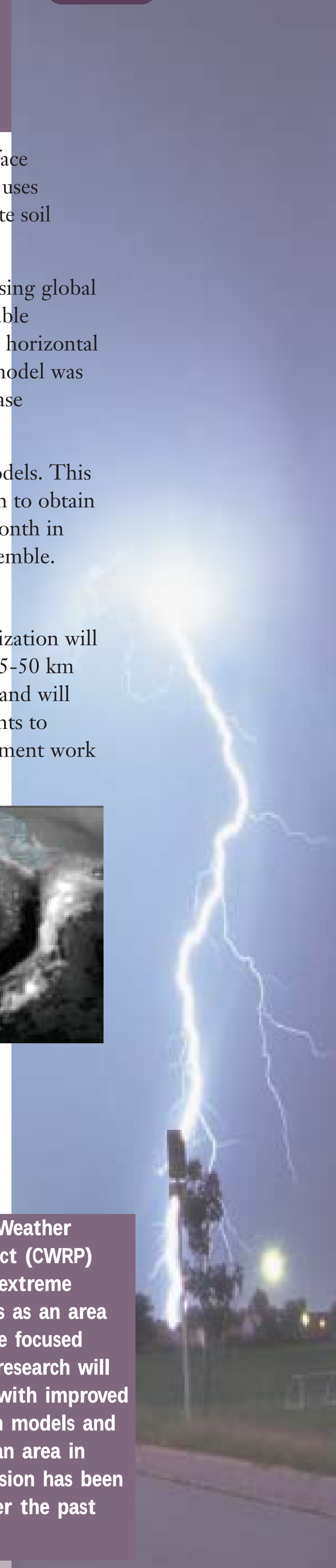
GEM-based high-resolution modelling was first attempted in the spring of 1997. Since then, the application of GEM has been extended to 'nowcasting' at the urban scale, and to dynamic extended-range forecasting on monthly to seasonal time scales. The essence of the Division's approach is to develop a single, highly efficient meteorological and environmental prediction model that can be reconfigured either to run globally at uniform-resolution, or to run with variable resolution over a global or limited domain with the highest resolution focused over an area of interest.

Model Operational Implementation at Canadian Meteorological Centre (CMC)

There have been continual improvements to the GEM system over the past five years. The operational GEM model is now interfaced with a full complement of physical processes.

Major highlights are outlined below:

In February 1997, GEM (35km horizontal resolution) replaced the Regional Finite Elements (RFE) model for regional modelling up to 48 hours, twice daily. This was followed in September 1998 with the introduction of the variable resolution GEM – using a 24km horizontal resolution with 28 vertical levels, with an uniform high-resolution area covering North America and adjacent oceans.



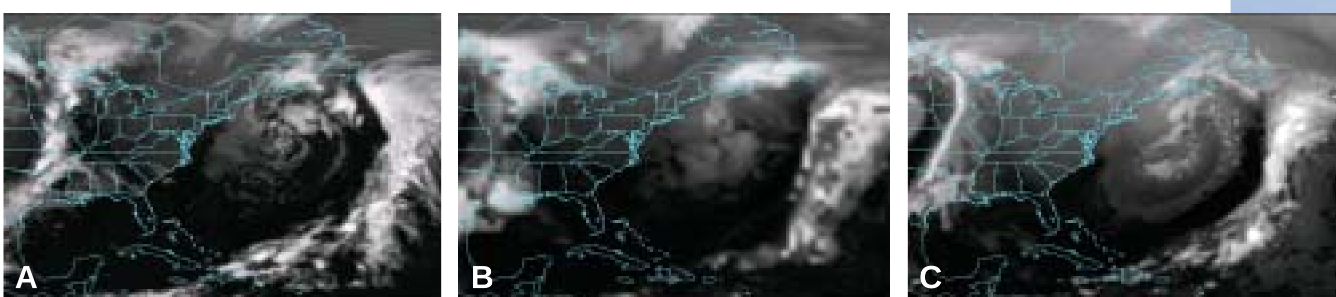
The current regional model uses a state-of-the-art convection and condensation scheme and surface modelling system. The present surface modelling system was introduced in September 2001 and uses vegetated land with snow cover, ice-free and ice-covered oceans and lakes, and glaciers to generate soil temperature and soil moisture.

In October 1998, GEM became operational for global modelling up to 240 hours (10 days), using global uniform resolution at 0.9° with 28 vertical levels spanning the troposphere. In July 1999, variable resolution GEM was implemented for high resolution modelling up to 30 hours with a 10 km horizontal resolution with 35 vertical levels covering 2 windows over eastern and western Canada. The model was further improved in February 2001 with a state-of-the-art convection and mixed ice-water phase condensation scheme.

Monthly and seasonal forecasts are produced using ensemble methods employing multiple models. This is possible because of the considerable effort that was put into the development of an approach to obtain model climatologies in seasonal and monthly contexts. Monthly forecasts are issued twice a month in ensemble mode, and seasonal forecasts are issued four times a year using the multi-model ensemble.

Future Implementation of the Medium Range Forecast Global GEM

The rapid increase in computer power that is expected in the next few years and model optimization will produce an increase in the global horizontal and uniform resolution of the model - to about 35-50 km horizontal resolution. The vertical resolution will also be augmented (to at least 60-80 levels) and will cover the troposphere and stratosphere. Together with this increase in resolution, improvements to almost every aspect of the physical parameterizations are proposed. The research and development work on this GEM configuration has already started.



Panel A shows the satellite observed long wave radiation; panel B shows the forecast of the operational GEM model at 100km horizontal resolution; panel C shows outgoing long wave radiation (a good indicator of cloud cover) for the 1-day forecast at 0000UTC 2 November 2000, using the new experimental GEM at 35km uniform horizontal resolution.

High-Resolution Numerical Weather Prediction Research

The Canadian Weather Research Project (CWRP) has identified extreme weather events as an area deserving more focused research. This research will be supported with improved high-resolution models and diagnostics – an area in which the Division has been very active over the past five years.

RPN has been successful, working in collaboration with McGill University, in obtaining CFCAS funding to pursue further R&D in high-resolution numerical weather prediction. The Division has also worked with universities and other laboratories to support development of a high-resolution modelling community. The group has made significant progress especially in simulations for wind energy industry applications. The latest study *"Long-term research and development needs for wind energy for the time frame 2000 to 2020"* of the International Energy Agency (the energy forum for 25 industrialised countries established in 1974) highlights two weather related research topics as crucial to the future deployment of wind energy. These include the use of weather forecasting techniques to identify the optimal locations for wind farms (on land and offshore), and electricity production forecasts from 6 to 48 hours. **RPN believes that investing in these areas will have a concrete and measurable impact on the energy sector in Canada.**

Recently, the Division has made significant progress in high-resolution mesoscale forecasting and simulation for wind energy industry applications. This has resulted in partnerships with acclaimed world experts in the field of wind energy prospecting. Our recognition in the field of wind energy numerical modelling is increasing steadily. The Banque Africaine de Développement has mandated us to participate as a principal scientific investigator in the assessment of the wind energy potential of Africa.

To validate high-resolution models and increase our expertise in lake, mountain, arctic and ozone meteorology, the Division has been supporting several high-resolution world class and national field projects. These field projects include the Montreal-96 Experiment on Regional Mixing and Ozone (MERMOZ), the First ISCCP Regional Experiment - Arctic Cloud Experiment (FIRE-ACE), the Mesoscale Alpine Programme (MAP) and the Effects of Lake Breezes On Weather (ELBOW) experiment using GEM model at urban scale resolution (2.5km).

Coupled Modelling for Environmental Prediction

One of the key challenges facing RPN and MRB is to align weather, climate and air quality models to allow for an integrated environmental prediction system. In support of this long-term objective, the Division has been active in exploring the coupling of a variety of numerical prediction models.

RPN has the expertise and software to interface atmospheric models to hydrologic models and to a sea-ice model, and has successfully applied coupled hydrologic modelling to different regions, including the Rockies, the Alps, St-Lawrence River and Ontario. A collaborative effort with Dr. J. McConnell at York University is also addressing the challenges of a comprehensive coupling of GEM to an atmospheric chemistry model.

In the area of wave modelling, the Division has developed and validated wave models, developed a system for the assimilation of synthetic aperture radar wave observations into a wave model, tested higher resolution versions of wave models, and implemented and tested shallow water wave dynamics in wave models. **These developments have made possible the creation of a series of operational wave forecast products for the East and West Coasts of Canada.**

The MSC has established an ACSD research presence in Halifax, Nova Scotia, and has joined with other government R&D programs to support an environmental prediction capability in the Atlantic Region. The Atlantic Environmental Prediction Research Initiative (AEPRI) integrates expertise from a wide range of disciplines and builds on MSC's scientific and technical capabilities in both research and operational modes.

The Canadian Foundation for Innovation has awarded a total funding of $3.6 million to the Marine Environmental Prediction System (MEPS) project. This project has the descriptive title "Marine Environmental Prediction System (MEPS) for real-time observation, prediction & visualization of physical, chemical & biological processes in marine ecosystems on continental shelves & in coastal inlets". AEPRI is playing a key role in the coupled atmosphere/ocean/ biology/chemistry/ecosystem high-resolution observing and numerical modelling demonstration project for Lunenburg Bay, Nova Scotia.

Collaboration with the region's government, university, and industry experts that specialize in atmospheric and oceanic sciences and operational meteorology has been fruitful and has lead to the transfer, evaluation and **implementation of Canada's first operational storm surge prediction and water level alert system.** This is based on Dalhousie University's 'first generation' coastal ocean data assimilation and prediction system, driven by CMC's regional forecast model for surface pressure and winds. Through AEPRI, this system has been implemented at the Maritimes Weather Centre where it is a new operational guidance product that helps protect life and property during storm surge events. **This system has also served as an important component in the recent Climate Change Action Fund project on Prince Edward Island sea level rise.**

Post-Processing Research

When a model changes, weights are added to de-emphasise old model forecasts in relation to new model forecasts. The weighting scheme is also applied to seasonal transitions. The equations are updated weekly with the latest model output data. The UMOS statistical adaptation system has been implemented for temperature, winds and 6-h probability of precipitation forecasts at approximately 700 Canadian stations. UMOS is based on the operational GEM regional model outputs, but the dataset can be applied in support of the regional air quality programs. These forecasts are generated using state-of-the-art techniques that optimize selection of predictors from a large pool. An aviation package has been developed to provide guidance for aviation impact variable (AIV) forecasts. This package includes freezing level, in-flight icing, clear air turbulence, mechanical turbulence, cloud bases and tops, and tropopause height.

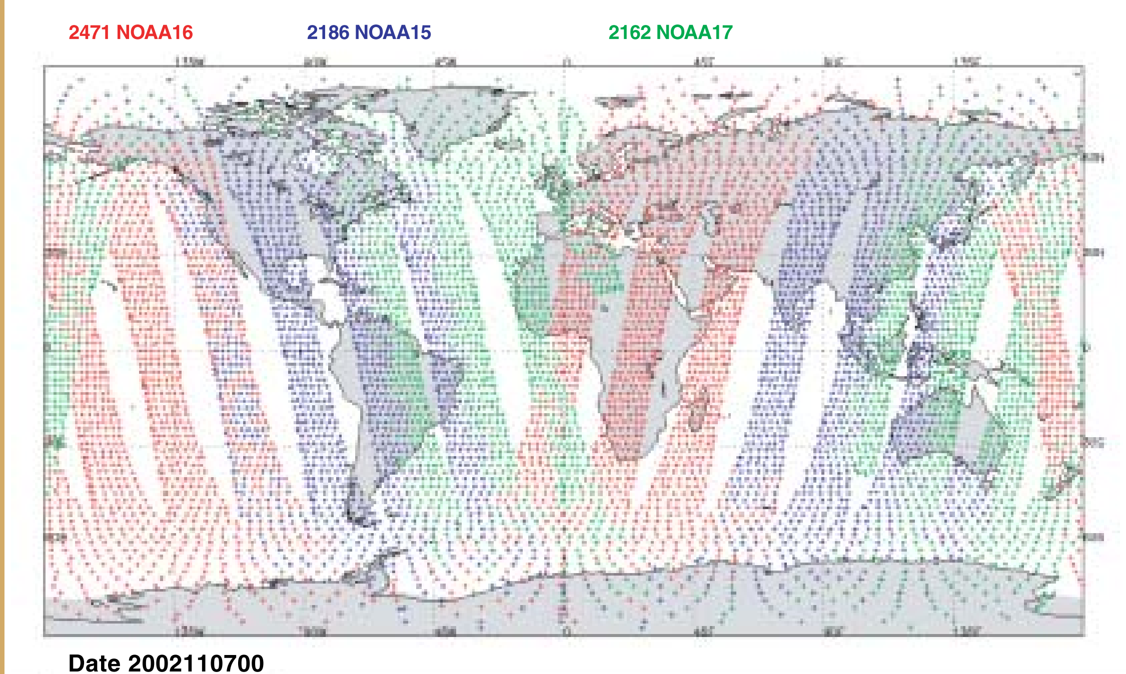
RPN's statistical post-processing approach, Updateable Model Output Statistics (UMOS) is designed to enable data management and preparation in near real time. This allows new model output to be effectively used after a model is implemented.

Data Assimilation and Satellite Meteorology (DASM)

The Data Assimilation and Satellite Meteorology Division (DASM), in partnership with the Canadian Meteorological Centre (CMC), carries out data assimilation and remote sensing R&D activities to support continuous improvement to operational numerical weather prediction (NWP). These products play a central role in MSC weather services.

DASM carries out its data assimilation activities to support MSC's climate and air quality research. The Division also conducts R&D on remote sensing of sea ice to support the Canadian Ice Service, and data assimilation and remote sensing research in support of strategic planning for the MSC's weather observing networks that are operated by the Atmospheric Monitoring and Water Survey Directorate (AMWSD).

The following is an overview of DASM accomplishments from 1996 to the present, the status of current projects, and its near-term plans.



Satellite sounder radiances assimilated directly into CMC NWP models in a typical 6 hour period.

Variational Data Assimilation

The central thrust of the data assimilation R&D program over the past five years was the development of a variational data assimilation system for operational use in the Numerical Weather Prediction (NWP) program at CMC.

From the outset, the system was designed for use in both the global data assimilation system (GDAS) - used to launch medium-range weather forecasts extending from 3 to approximately 10 days - and the regional data assimilation system (RDAS) - used to launch detailed short-range forecasts extending out to 48 hours. There were three main objectives in the development of the variational data assimilation system:

- Firstly - more effective assimilation of measurements that are indirectly related to the prognostic variables of the forecast model, especially remote sensing measurements; (Making effective use of these data is particularly important due to the explosion that is taking place in the diversity and quantity of remote sensing data from space- and ground-based platforms.)
- Secondly - more effective analysis of the rapidly growing atmospheric structures that are associated with major storms and "bust forecasts". (Accomplishing this requires an assimilation system that employs the physics captured in driving the NWP model to assimilate measurements in a way that depends on the details of the meteorological situation (flow-dependence).)
- Thirdly - more effective use of high-resolution time series measurements, such as hourly observations from radar wind profilers and automated measurements from commercial aircraft.

The first step in this program was to develop a three-dimensional variational data assimilation system (3D-Var). This system was aimed at meeting the first objective above, and providing a base on which to build a four-dimensional data assimilation system (4D-Var). A 4D-Var system will meet the second and third objectives. The first operational version of the 3D-Var was implemented in the GDAS (Global Data Assimilation System) in June 1997, and in the RDAS (Regional Data Assimilation System) in September 1997. It was first designed to resemble the optimum interpolation (OI) assimilation system that it replaced as closely as possible. This allowed for the validation of the assimilation algorithm without revisiting all the elements of the data pre-processing (such as radiosondes, surface reports, satellite temperature retrievals, etc.) The analysis was carried out on the 16 constant-pressure surfaces of the OI, with a similar representation of the short-range forecast error statistics.

In June 1997, the GDAS was driven by the spectral finite element (SEF) model, which was replaced in the GDAS by the uniform-resolution version of the Global Environmental Multi-Scale (GEM) model in 1998. Since the variable-resolution configuration of GEM had been introduced earlier for operational regional forecasts, this completed the implementation of the unified short- and medium-range forecasting and data assimilation system which was the strategic objective of MRB and CMC since the early 1990's.

In June 2000, a new version of 3D-Var was implemented in which the analysis increments were computed directly on the GEM η vertical coordinate (3D-Var-η). The 3D-Var-η included a new forecast error covariance model and forecast error statistics that were based on lagged 24-48 hour forecast differences (the so-called "NMC method"). The first major change to the data that was assimilated into the GDAS was made in September 2000 when vertical temperature profiles retrieved from radiance measurements by the TOVS system (familiarly known as SATEMS) were replaced by direct assimilation of radiance measurements from a limited number of TOVS microwave channels.

At the same time, automated wind observations from commercial aircraft known as ACARS (Aircraft Communication Addressing and Reporting System in the U.S. and AMDAR internationally) were introduced into the system. The 3D-Var-η, including TOVS radiances and ACARS/AMDAR winds, became operational in the RDAS in January 2001. Aside from the replacement of SATEMS by radiances, the treatment of other types of data was basically the same in the first version of the 3D-Var-η as it was in the pressure-level 3D-Var.

Work in 2001 focused on assimilating new data types and improving the treatment of radiosonde and surface observations and led to a second major upgrade to the 3D-Var. The major elements upgraded included the assimilation of:

- Radiosonde temperatures (in place of geopotential);
- Significant-level data from radiosondes;
- Surface pressure and temperature from surface stations, ships, buoys, etc. (in place of a calculated 1000 hPa geopotential);
- Dropsonde temperatures and winds;
- Additional TOVS channels that see lower into the atmosphere; and
- The introduction of variational quality control.

The new version of 3DVAR was implemented in the GDAS and the RDAS on December 11, 2001. At the same time, an upgrade to the gravity wave drag parameterization was introduced in the GEM global configuration in the GDAS. This produced a marked improvement in the quality of the operational CMC global forecasts that was clearly seen in comparisons of verification scores with those of other NWP centres. A number of journal papers were published on the development process of the 3D-Var system.

Development of the tools necessary to extend the 3D-Var system to 4D-Var was undertaken in parallel with the development of the 3D-Var itself. A major component of this effort was the development of the tangent linear version (TLM) of the GEM model and its adjoint, which began in September 1994. With a view to the long term, the decision was made from the outset to develop 4D-Var around the GEM model, which did not become operational until 1997.

Development of the TLM and adjoint of GEM required investigation of a number of new issues associated with semi-Lagrangian schemes, since previous work at other NWP centres had focused on Eulerian models. These investigations were reported in a number of journal papers. The TLM and adjoint models have been modified to follow significant changes in the GEM model, such as a new horizontal staggering, performance update and 32-bit implementation. Recently, the tangent linear and adjoint models of the distributed memory version of GEM have been achieved and are currently being optimized.

In addition to the TLM and adjoint of the GEM dynamical core, a set of simplified physical parameterizations and their adjoints (vertical diffusion in the surface layer, gravity-wave drag, and stratiform precipitation) were developed. These are expected to be sufficient for a first implementation of an operational 4D-Var. These parameterizations have been used for experiments with a sensitivity analysis system for identifying rapidly growing analysis errors on a routine basis at CMC. The next step, to begin in 2002, is to conduct 4D-Var experiments based on the full set of observations currently used in the 3D-Var. **The goal is to implement a 4D-Var in the global data assimilation system in 2003.**

Mesoscale Data Assimilation

The Division has studied the problem of variational assimilation of precipitation data in collaboration with researchers from other institutions – examining issues related to parameterization of stratiform and convective precipitation and issues of balance. Work on mesoscale analysis and assimilation of radar data has progressed in collaboration with McGill University. This work has ranged from the retrieval of dynamic and thermodynamic variables to the four-dimensional assimilation of bistatic Doppler velocities and reflectivity data, using a meso-γ model as a weak constraint.

Data assimilation on the mesoscale is an important requirement for the future development of operational forecasts, and work is underway in a number of areas to address the scientific challenges involved.

Ensemble Prediction and Ensembles in Data Assimilation

Research towards the development of an ensemble Kalman filter (EnKF) began in 1996. This filter is envisaged as the assimilation engine for medium-range ensemble prediction and ultimately for use in ensemble prediction at shorter time scales.

The EnKF is an intrinsically flow-dependent (4D) algorithm that is planned to replace the current 3D (OI) analysis algorithm in the operational ensemble prediction system. In principle, it also has the capability of directly assimilating measurements that are indirectly related to model prognostic variables. The first EnKF experiments were performed using a 3-level T21 quasi-geostrophic model and simulated observations. It was found that ensembles with O(100) members were sufficient to describe local, anisotropic, baroclinic correlation structures accurately.

Next, the Division developed a method of parameterizing model error and using innovations to estimate the model-error parameters. A prototype analysis algorithm in which the observations were organized into batches and assimilated sequentially followed as the next step. The ensemble of background fields is updated at each step of the sequential algorithm and, as more and more batches of observations are assimilated, it evolves to become the ensemble of analysis fields.

Most recently, the sequential EnKF was used to assimilate simulated observations into a dry version of the GEM model. The model had a 144 by 72 horizontal grid and 21 levels that included topography, and the use of simple forcing and dissipation proposed by Held and Suarez. The extension of the experiments to real observations using a medium-resolution version of GEM with a complete set of physical parameterizations is planned for 2002.

Satellite Meteorology

DASM carries out satellite meteorology R&D applications of satellite data for Numerical Weather Prediction (NWP), and for severe weather research.

Work on applications of satellite data for NWP has been carried out in close cooperation with the variational assimilation development team. A major focus has been on issues related to the accuracy of fast-parameterized forward models for satellite instruments. These are used in assimilation systems to calculate the expected values of observations from the NWP model state; and on quantifying systematic biases in innovations (differences between measurements and their observed values that are calculated from a prior model forecast), and developing algorithms to compensate for these biases. This development work was essential to the operational implementation of direct assimilation of TOVS microwave radiances in the GDAS in September 2000 and in the RDAS in June 2001. During the summer of 2001, work focused on assimilation of lower peaking AMSU-A radiances over water. These additional channels are part of the major upgrade that was undergoing parallel testing in October 2001.

GOES imager data have been assimilated indirectly at CMC since 1993 in the form of statistically derived humidity profiles. This technique was improved in 1997 to include more upper tropospheric information from the water vapour channel using a technique based on radiative transfer simulations. More recent work on GOES is aimed at directly assimilating the surface and water vapour imager channels.

Division scientists have used comparisons between satellite observations and model forecasts to identify systematic model errors, as a tool for improving model parameterizations related to the water cycle. GOES imager data have also been used to study differences between observed cloud properties and cloud properties

from model forecasts. GOES imager data has also been used to vertically integrate water vapour retrievals from U.S. Defence Meteorological Satellite Program (DMSP) platforms, and to identify deficiencies in the model humidity field in the lower troposphere.

Division scientists have played an active role in satellite data assimilation R&D in the international community. A Division scientist chairs the NWP sub-working group of the International TOVS Working Group (ITWG) , that brings together specialists from all major NWP centres, satellite operating agencies, and universities to collaborate on assimilation and other applications of satellite sounder data. Through the ITWG, division scientists led an international intercomparison of fast-parameterized forward models for TOVS measurements, as well as an international intercomparison of simulated TOVS radiances by the line-by-line (LBL) radiative transfer models on which the parameterized models are based.

Division scientists have made several contributions to the development of the RTTOV parameterized forward model that is used operationally for direct assimilation of TOVS and ATOVS at several NWP centres, including CMC. RTTOV has, in essence, become an international community model, and has been extended to model measurements by a number of other instruments. The capability to simulate radiances from the Special Sensor Microwave Imager Sounder (SSMIS) has been added to RTTOV, making it a new instrument on the U.S. DMSP satellites, and has resulted in major improvements to the parameterizations used for simulating radiances in the 183 GHz water band.

A line-by-line modelling (LBL) capability is being maintained and upgraded for use in a variety of applications. The LBL simulations have been used in development and validation of fast models as well as a flux parameterization for the 1 mm CO_2 band, which is now used in the Canadian GCM. **Applications of satellite data to severe weather research have focused on the link between lake breezes and convective severe weather in southern Ontario.** This work has been carried out in close collaboration with the Cloud Physics Research Division. The Division has operated a GOES reception station that has collected data sets for numerous cloud physics field programs, and has collected polar orbiter satellite data from operational MSC reception stations that have been used by researchers across ACSD.

Middle Atmosphere Data Assimilation

Research on assimilation of data into the Canadian Middle Atmosphere Model (CMAM) began as a multi-branch ACSD initiative in 1996. Initially, progress was slow due to a lack of resources until 2000, when the project was rejuvenated as part of the Global Climate and Chemistry (GCC) project that was led by Prof. T. Shepherd at the University of Toronto, with full-time participation of a DASM data assimilation specialist as a co-investigator.

The overall objective of the GCC project is to study the interactions between the chemistry of the atmosphere and global circulation, with a focus on long time scales. The data assimilation component of the project will challenge CMAM predictions of the day-to-day state of the atmosphere with observations as a complement to comparisons of the climate of the model with climatologies derived from observations.

CMAM is now running in continuous data assimilation cycles with a lid at 0.0007 hPa (90 km). The assimilation engine is a version of the 3D-Var-h that is very close to that used operationally. Consequently, it will be possible to take advantage of future upgrades to the operational system. The system is using all types of "conventional" data that are currently used operationally, including direct assimilation of TOVS radiances. Work is under way to assimilate TOVS channels that sense the upper stratosphere and lower mesosphere, which are not used in the operational NWP system with its lid at 10 hPa (30 km).

Work over the next couple of years will focus on assimilation of new satellite measurements that sense the dynamics of the upper stratosphere and lower mesosphere. It will also focus on the use of satellite measurements of atmospheric constituents. **This project is attracting considerable international**

attention since it is poised to leapfrog over other middle atmosphere data assimilation programs by assimilating data into an atmospheric model that has full interactive chemistry and includes the mesosphere.

Satellite Remote Sensing of Sea Ice

DASM has contributed to the development of semi-automated techniques for classifying ice types using RadarSat synthetic aperture radar (SAR) data. This has been done using statistical methods that compile and update the radar signatures of different ice types from thousands of RadarSat SAR images that have been used operationally by CIS since 1997.

It is planned to run the algorithm against the entire record of RadarSat SAR data for the Arctic in order to determine annual changes in sea ice. To support ice R&D, DASM has championed the development of SAR image archiving systems at CIS. Financial support has been obtained from CIS and the Canadian Space Agency to produce an archive of processed SAR images, which is a unique resource for sea ice research in Canadian waters. Work is being carried out on data fusion techniques (using RadarSat, passive microwave data from the SSM/I instrument on the US DMSP satellites, and visible/infrared imagery from the AVHRR instrument on the NOAA polar orbiting satellites). This is for improvement of sea ice classification, and the 85 GHz microwave emission from sea ice is being studied to estimate thickness of new ice from the onset of ice growth up to about 15 cm thickness.

Use of Data Assimilation for Observing Network Planning

Work recently began on applications of data assimilation techniques in support of strategic planning for the operational weather-observing network managed by AMWSD. Research is focused toward the development of techniques to identify areas of rapidly growing forecast error for use in targeting observations, and on techniques for evaluating the effect of alternative network configurations.

Work in this area will build on the development of both the EnKF and the 4D-Var. The program is being carried out in coordination with THORPEX (The Observing-system Research and Predictability Experiment) under the auspices of the World Weather Research Program (WWRP). Division scientists are members of a number of THORPEX planning committees. **Research is also underway to evaluate the usefulness of water vapour information that is retrieved from ground-based Global Positioning System (GPS) receivers.** This work is being carried out in partnership with the Geodetic Survey Division of Natural Resources Canada, which operates GPS stations across the country as control points for the Canadian topographic mapping system and for glacial rebound and crustal movement studies.

Cloud Physics Research (ARMP)

The role of ARMP is to conduct applied research in cloud and precipitation physics, with a view to developing direct applications to reduce the impact of weather on Canadians.

The Division is primarily orientated towards process studies with a heavy emphasis on measurement methodologies and technologies. However, important computational and theoretical investigations on radiative transfer, cloud modelling and cloud microphysics are also being undertaken. The Division currently maintains research for the following:

- Environmental Research Aircraft Facility
- National Radar Plan Implementation

- Radar meteorology
- Severe weather research
- Cloud physics applied to meteorology and climate applications
- Aircraft icing research program
- Cloud modelling
- Cloud Radiative transfer modelling

The Division's accomplishments in these areas over the period 1996-2001 are discussed in the following paragraphs.

Environmental Research Aircraft Facility

The Environmental Research Aircraft Facility (ERAF) provides support for MRB, AQRB, and CRB experimental research programs. This support includes developing instrumentation, providing advice, and in many cases collaborating in the design and planning stages of scientific experiments. The NRC Convair-580 aircraft is the best-instrumented aircraft in the world for in-situ microphysics measurements.

In the past five years, the ERAF has expanded the measurement capabilities of the National Research Council's (NRC) Convair-580 and Twin Otter aircraft by adding in excess of $2M of new equipment, through strategy capital funding. An informal arrangement with the Canadian Forestry Service (CFS) has been used to develop a small, inexpensive Cessna platform for certain specific requirements. **These efforts have led to world-class measurement capabilities in cloud microphysics storm structure and air chemistry.** These capabilities will soon include microwave radiometry for climate applications. The ERAF has also been heavily **involved in the evaluation and calibration of state-of-the-art airborne instrumentation, and has forged relationships with world experts to tackle cutting edge instrumentation issues.** This has led to a high level of international respect and confidence in MSC's airborne measurements, especially in the area of cloud microphysics.

Important research programs that were conducted by the ERAF during the previous five years included MERMOZ and MERMOZ II (Montreal-96 Experiment on Regional Mixing and Ozone), FIRE.ACE (First ISCCP Regional Experiment – Arctic Cloud Experiment), AIRS (Alliance Icing Research Study), the Third Canadian Freezing Drizzle Experiment, MITE (Metals in the Environment), Hurricane 2000, and a variety of CRB remote sensing projects for snow pack and soil moisture measurements.

During 2001-2002, the ERAF conducted several major field projects including ELBOW (Effects of Lake Breezes On Weather), PACIFIC 2001 (particulate matter and ozone study), Hurricane 2001 (flight into Hurricane Karen while it was making a transition into an extratropical storm), CRYSYS 01/02 (validation of snow cover inferred from EOS satellite data) and SMR 01/02 (soil moisture measurements using low frequency microwave radiometers). A full slate of projects is scheduled for the ERAF through to 2004.

National Radar Project (NRP) Implementation

Significant technology from the R&D at the King City Radar has been transferred (hardware, software and signal processing) to the National Radar Project (NRP), and to the international community. Canada is a world leader in the technical transfer of radar meteorology research into operational forecast products.

Hardware developments adopted by the NRP have provided high quality (i.e. low phase noise) radars at an affordable cost, and allowed for the conversion of the entire radar network to Doppler technology. **The King City radar stood alone and led internationally, for almost a decade, in the use of intensive spectral processing for radar signals.** This approach has been adopted by the NRP. Random phase processing, which mitigates the range ambiguity resolution of Doppler radars was pioneered at King City. This approach allows the Doppler radar to double its range. This research inspired CAR/National Severe Storms Laboratory scientists, and others to develop similar pulse modulation schemes to perform the same function on the NEXRAD radars.

The development of automatic severe weather radar algorithms has formed the basis for using Doppler radar technology in the weather office, particularly in the MSC where only one forecaster is available to survey the Doppler data from seven or more radars. The access to radar products was prototyped in a display system called KARDS (King Automated Radar Display System) and has lead to the current and future generations of radar display stations for MSC.

Central to the NRP has been the development of Unified Radar Processor (URP) software. Version 1 contained the basic methodologies described above and is currently operational. Version 2 focused on severe weather algorithms and became operational in the summer of 2002. Version 3 will focus on quantitative precipitation estimation and will be operational in the fall of 2003. These software versions were developed as a result of significant technical transfer of research performed over the past 15 years.

Radar Meteorology

ARMP has pioneered Doppler radar-based studies of the detailed nature of severe winter storms in Canada. This has included developing a conceptual model that produced new insights into the spatial and temporal structure of frontal zones, – including a more complete explanation for the nature of frontal structures and the associated precipitation in these systems.

This is an area where large-scale models are limited in their ability to handle cloud and precipitation fields. The Division's work has highlighted the importance of microphysics-driven thermodynamic and dynamical processes and feedbacks (for example, those established by melting snow just above the upper 0°C layer) in controlling the organization of precipitation cores, as well as the relation of precipitation rate with precipitation type. Other important research lead to the development of methods for quality assessment of radar data and algorithms, including advanced recognition of non-meteorological targets such as birds, ground targets, attenuation, and bright bands. Division R&D also lead to the development and operational implementation of a velocity azimuth display (VAD) wind module that estimates its own errors.

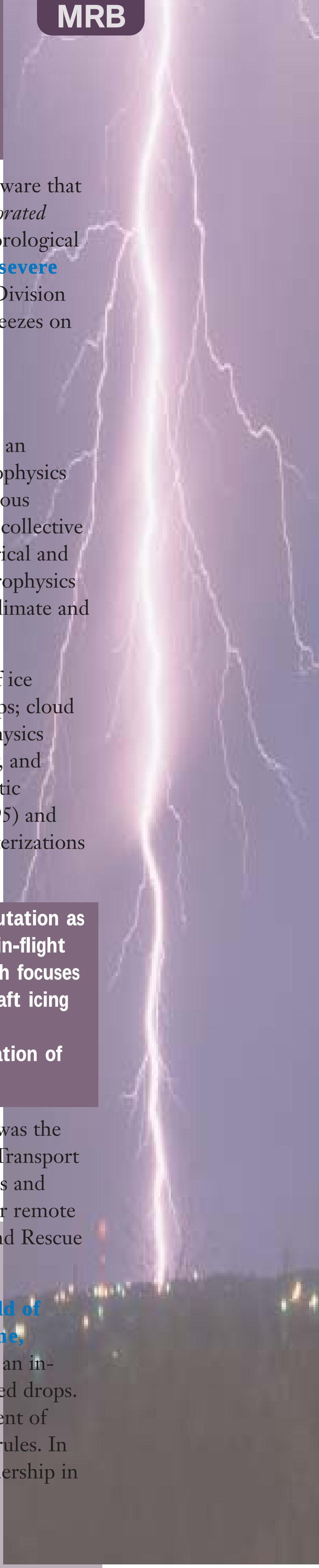
Division scientists initiated and participated in the Sydney 2000 Olympic nowcasting project where the knowledge from King City R&D was transferred to the meteorological service in Australia. They subsequently changed the way they operate their Doppler radars by implementing dual pulse repetition frequency (PRF) scanning and Doppler ground clutter filtering.

Severe Weather Research

ARMP severe weather research is focused on improving detection and prediction of summer and winter severe weather. This includes research in the use of ground and satellite based remote sensors and in-situ data to better detect severe weather phenomena such as tornadoes, strong winds, heavy precipitation, and transportation hazards.

Division scientists planned, and led the Effects of Lake Breezes On Weather (ELBOW) experiment (summer 2001). The project goals were to determine the way in which lake breeze circulations associated with the Great Lakes affect the location, timing and intensity of thunderstorms and severe weather in southwestern Ontario, and to evaluate and improve current methods of forecasting severe weather associated with lake breezes.

ARMP scientists were also heavily involved in the Hurricane 2000 and 2001 programs, where **a fully instrumented research aircraft was flown through two extratropical hurricanes. The objective of these flights was to understand the dynamics associated with the storms during these periods of rapid change.** Ongoing studies include severe weather climatologies for hail, freezing precipitation, tornadoes and radar-derived severe weather.



The Division is currently supporting Version 5 of the Forecast Production Assistant (FPA) software that is being used commercially by *Weathernews International* (worldwide) and *Surface Systems Incorporated* (USA). Scientists are modifying this code to support several severe weather research and meteorological case studies. Once these modifications are complete, **FPA will be one of the most advanced severe weather case study tools in the world.** The modified code is already being used to support Division research programs such as AIRS (Alliance Icing Research Study), ELBOW (Effects of Lake Breezes on Weather), and AVISA (Airport Vicinity Icing and Snow Advisor).

Cloud Physics Applied to Meteorology and Climate Applications

ARMP continues to be a world-leading group in cloud physics, and its scientists have been extremely active in the application of cloud physics to meteorological and climate issues.

During the past decade, division scientists have collected an extensive and unique world-class data set of in-situ microphysics measurements. The data was collected during the numerous experiments that the Division has been involved in. The collective data set is extremely useful for application to meteorological and climate studies. These data sets serve to help validate conceptual and numerical models of microphysics and dynamics, and are well suited for the development of microphysics parameterizations for climate and numerical weather prediction applications.

Several important microphysics studies have recently been completed including: climatology of ice particle shapes observed in stratiform clouds; ice crystal concentration-temperature relationships; cloud water-temperature relationships; large droplet formation through isobaric mixing; and microphysics characteristics of mixed phase clouds. In addition, several significant studies of cloud chemistry, and clouds and climate have been published, based on measurements made during the North Atlantic Research Experiment - NARE (1993), Radiation, Aerosol and Cloud Experiment - RACE (1995) and FIRE ACE -Arctic Cloud Experiment (1998). These studies have direct application to parameterizations used in Canadian numerical weather prediction and climate models.

Aircraft Icing Research Program

MSC has established a reputation as a world leader in aircraft in-flight icing research. This research focuses on developing better aircraft icing forecasting techniques and improving the characterization of icing environments.

During the past decade, there has been significant international attention to the problem of in-flight aircraft icing as a hazard to commercial aviation. This attention resulted because of several aircraft disasters in which icing was the primary cause. The division scientists planned, organized and led the second and third Canadian Freezing Drizzle Experiments, CFDE, (winters 1996/97 and 1997/98) and the Alliance Icing Research Study (AIRS) during 1999/2000. AIRS was the first project of the Aircraft Icing Research Alliance (AIRA), of which MSC, NRC, NASA and Transport Canada are members. Research objectives included developing improved forecasting techniques and characterizing the icing environment. AIRS objectives added the development of techniques for remote detection of aircraft icing at airports. Funding sources included Boeing, the National Search and Rescue Secretariat, NASA, the Federal Aviation Administration (FAA), and Transport Canada.

Division scientists have jointly published 20 journal and 40 conference papers in the field of aircraft icing. They have implemented a new diagnostic in-flight icing forecasting scheme, undertaken new climatological studies on the occurrence of freezing precipitation, and created an in-depth characterization of aircraft icing environments associated with small and large supercooled drops. Finally, they are heavily involved with Transport Canada and the FAA regarding the development of guidelines for commercial aircraft operating in icing conditions and possible new certification rules. In 2002, the lead scientist (Dr. George Isaac) was presented an EC Citation of Excellence for leadership in this field.

MSC researchers are committed to developing an airport weather warning system that will use satellite and radar measurements, numerical model data and a number of other surface instruments (POSS, radiometer, etc.) to detect and forecast hazardous precipitation, icing, winds and ceilings above airports. Development of such a system is expected to take 5 years, and the first prototype will be tested during AIRS II during the winter of 2003.

Cloud Modelling

Two sequential aircraft icing forecast algorithms have been developed, validated and implemented operationally in GEM in the last five years. This has lead to significantly better forecasts of cloud and icing conditions compared to the previous cloud forecast model.

The most recent algorithm developed is the mixed phase icing scheme. It contains diagnostic cloud and icing forecasts. It is currently operational in GEM-HIMAP and is being implemented operationally in GEM global. These cloud and icing models have been extensively used to support the field phases of the Canadian Freezing Drizzle Experiment (CFDE), AIRS and FIRE.ACE projects. ARMP has developed comprehensive and unique forecast validation methodologies. These include intercomparisons of model forecasts with satellite, surface and aircraft in-situ measurements.

Cloud Radiative Transfer Modelling

ARMP has been active in the development and validation of radiative transfer models for use in large-scale circulation models that account for interactions between radiation and unresolved cloud fluctuations.

The initial algorithm computed solar albedo and transmittance for single layer clouds, but was insufficient for use in large-scale models that partition the atmosphere into arbitrary vertical layers. To remedy this problem, a multi-layer version of the solar transfer algorithm was developed and tested extensively against 3D Monte Carlo simulations. This lead to the definition of a main thrust in climate/radiation research, one in which both unresolved horizontal fluctuations in cloud and vertical overlap are considered together. In collaboration with CRB scientists, the solar and longwave multi-layer algorithms have been added to the CCCma-GCM, and sensitivity tests are being conducted.

Science Assessment and Integration Branch (SAIB)

Science advisors within the Science Assessment and Integration Branch are focused on key atmospheric issues and provide science advice and guidance to a full range of policy development activities, and scientific information to educate Canadians regarding the science of atmospheric issues.

Introduction

The Science Assessment and Integration Branch (SAIB) has probably evolved more, over the past five years, than the other Branches within ACSD. Prior to January 1999, the Branch was located within the policy arm of the Meteorological Service of Canada (MSC). In January of 1999, the Branch was transferred from the policy arm of MSC to its research side to ensure strong linkages with the scientists involved with the leading edge research associated with critical atmospheric issues.

As changing patterns within the atmosphere became identified as 'issues', the role of the Branch expanded and the bridge between science and policy was strengthened and reflected the new considerations associated with risk assessment (what exactly is the scientific problem?) and risk management (what should we do about it?). Recognizing the 'oneness' of our atmosphere and its integrated chemistry, physics and meteorology, individual science advisors are now working in broader units that are more relevant to policy considerations. The policy community is moving toward a more integrated approach to responding to problems associated with atmospheric pollution, with policies aimed at multiple and cross-issue benefits. This approach requires an understanding of how the issues are linked scientifically.

The Branch's air quality 'unit', for example, includes science advisors in particulate matter, ground level ozone and acid rain. The climate 'unit' includes science advisors in climate, climate change, and impacts of changing climate – including relationships between changing climate and stratospheric ozone depletion and the associated UV-B increases. Work is also undertaken on understanding options for responding and adapting to changing atmospheric conditions, including linkages with issues such as biodiversity, human health and water. Knowledge management and knowledge sharing are the key components of the work of the Branch.

The SAIB is mandated to provide:

- **Science assessments** (from broad, multi-year, multi-stakeholder-produced risk assessments to more narrowly defined, rapid turn-around analyses);
- **Ongoing science advice and guidance** to a full range of policy development activities; and
- **Scientific information designed to educate Canadians** regarding the science of atmospheric issues.

Science Assessments

The essence of a science assessment is to critically analyze and definitively judge the state of understanding on an issue that is inherently scientific in nature. It is a point-in-time evaluation of the existing knowledge base that highlights both areas of confidence and areas of uncertainty in the science.

A science assessment is not a research project that is aimed at generating new knowledge. It can, however, spur research to fill a known knowledge gap. Assessments communicate science to non-scientific audiences, policy makers, and stakeholders. They also serve to generate relevant feedback from these audiences to the scientific community.

Science assessments must satisfy a diverse and challenging set of requirements:

Firstly, scientific credibility is of the highest priority. The information base of the assessment must pass scientific peer review. The assessment itself must then undergo rigorous internal and external peer review. The requirement for scientific credibility serves the purpose of ensuring the policy community that it is receiving sound science advice. **Having met accepted standards of scientific excellence; the assessment becomes an invaluable resource for the scientific community.** It provides a highly credible synthesis of current science and an evaluation of current knowledge gaps, providing guidance on decisions regarding future research directions.

Secondly, assessments serve effectively as a mechanism for providing science advice to policymakers. Science assessments are generally written as successive reports, with each update going further than the previous one in presenting the science.

Thirdly, assessments provide a means of educating the general public, enabling citizens to make decisions about personal action and their level of support for government actions on an issue.

Atmospheric ‘issues’ of concern to Canadians range from those having local or regional application over relatively short time periods to global concerns that will have lifetimes in the order of centuries. The assessment of these issues, including the development of clear statements of the current state of understanding and the degree of confidence associated with them, will vary in process and timing. ‘Smog’, for example, is experienced at the local or regional level, over a duration of days and is often transboundary in nature. Understanding smog requires an understanding of the sources and nature of pollutants, the characteristics of the local terrain (urban or rural or valley etc.), and the current meteorology, as well as the chemistry and physics of the mixing and transport of the pollutants in the atmosphere. Climate change is a global issue, involving timeframes stretching into centuries and all components of the planet: hydrosphere, atmosphere, biosphere and geosphere. Other atmospheric issues lie between these end points and include acid rain, stratospheric ozone depletion and the long-range transport of hazardous air pollutants through the atmosphere.

Science assessments currently available from the Science Assessment and Integration Branch are included in the ‘Atmospheric Issues’ section. Upcoming assessments include, among others, those focused on particulate matter (2002 - North American), water availability (2003) and acid rain (2004).

Science Advice

The ongoing provision of science-based advice is a major component of the work of the Branch. The Branch provides science advice and guidance to:

- Policy community - throughout the policy development process for atmospheric and integrated air issues, and may range from input into briefing notes for senior administrators to text for inclusion within the steps of the legislative process; and

- Stakeholders - including other federal departments, provincial, territorial and municipal governments and Canadian negotiating teams at the international table.

The purpose of the advice is to clarify what is known, what is not known, where there is a high degree of understanding, and where there are uncertainties. During the risk management phase of policy development, SAIB may be asked about the likely effectiveness of certain policy directions. Examples of policy related questions include; "Will the policy help solve the problem?" and "Will the changes brought about by policy change be measurable and over what timeframe?". There is an opportunity at this stage of the process for science to play an active role as part of the solution.

Communicating to Educate Canadians

Good solutions can only be developed when the 'issues' are clearly understood by scientists, by policy makers, by stakeholders and by the public. SAIB provides opportunities and materials to engage these audiences - helping them to understand the science behind the issue and become part of the solution. This is an essential step towards enhancing the environment and working towards sustainable development.

Science advisors in the Science Assessment and Integration Branch interact directly with the media and provide media representatives with opportunities to discuss atmospheric issues and to ask questions and receive explanations and answers, either over the telephone or in broadcast mode. SAIB also provides various kinds of documents and materials ranging in levels of complexity to suit the audience. Materials range from multi-volume science assessments to information and teaching aids for the classroom. Through the Internet, SAIB's website provides easy-access opportunity for sharing knowledge, and directs audiences to relevant sources of additional information. **SAIB provides all of its products and services in a multilingual format that is updated regularly and responsive to new demands.**

The Atmospheric Issues

SMOG

Smog was the term originally applied to air pollution caused by a combination of smoke and fog - a predominantly wintertime phenomenon characterized by smoke particles and high levels of sulphur dioxide from the burning of coal or heating oil. However, it is now more commonly applied to the hazy conditions in the summer resulting from the action of sunlight on air pollutants such as nitrogen oxides and hydrocarbons (volatile organic compounds - VOCs) from combustion processes, especially the burning of fossil fuels by motor vehicles, power plants and other industries. This "photochemical smog" is characterized by the build-up of high levels of oxidants in the atmosphere (mainly ozone and nitrogen dioxide) and by very fine particulate matter.

Ground-Level Ozone

Ground-level ozone is a significant contributor to smog and air pollution.

Recent health and environmental studies in both Canada and the U.S. confirm that adverse health effects from ozone exposures are occurring at much lower concentrations than previously thought. Ground-level ozone and particulate matter (PM) together contribute to the smog issue, as these two pollutants have common precursors.

Ground-level ozone air quality initiatives include on a national level – The Canadian Environmental Protection Act (CEPA) – and on an International level - The Ozone Annex, under the 1991 Canada-United States Air Quality Agreement. SAIB is active on both national and international levels in supporting ground-level ozone air quality initiatives. The Branch provides science advice and guidance to decision-makers, plays an active role in international negotiations, contributes to relevant science assessments and National Ambient Air Quality Objectives (NAAQO), and facilitates the development of databases for input into atmospheric models.

SAIB was the lead for the **Canadian 1996 NOx/VOC Science Assessment** *"Ground-level ozone and precursor monitoring guidelines and implementation plan - Report of the Ambient Air Monitoring Working Group"* February 1997.

Particulate Matter (PM)

Managing and reducing PM and precursor emissions are key to reducing smog in Canada.

Based on current understanding, reductions of sulphur dioxide (SO_2) and oxides of nitrogen (NO_x) will provide regional improvements in $PM_{2.5}$ (particulate matter with a diameter of 2.5 microns or less), ground-level ozone and acid rain. This is only the first step to cleaner air. **The PM picture is not the same across Canada. There are distinct regional and seasonal differences. Multi-pollutant emission strategies need to be developed by region for all precursors.** Since atmospheric issues such as acid rain and ground-level ozone are linked by common pollutants or precursors, **multi-pollutant strategies need to address atmospheric issues in an integrated way.**

The fine fraction of PM ($PM_{2.5}$ or smaller) poses the greatest risk to human health. These particles have been associated with respiratory and heart problems, with the greatest risk to those who are most susceptible, including the young, the elderly and those with pre-existing cardio/respiratory ailments. In June 2000, a Canada Wide Standard was set for PM, and in June 2001 PM10 (particles less than 10 microns) was declared a toxic substance under the Canadian Environmental Protection Act (CEPA).

In response to policy needs and in service to Canadians, SAIB lead the assessment *'Precursor Contributions to Ambient Fine Particulate Matter in Canada' – May 2001*- in support of initiatives under Canada's Environmental Protection Act (1999) and the implementation of Canada Wide Standards for PM. The Branch also produced a summary of the precursor report for policy makers and Canadians. Both documents are available in english and french in hard copy and on the SAIB's website. This report identifies the principal precursors to $PM_{2.5}$ as sulphur dioxide (SO_2), oxides of nitrogen (NO_x), ammonia (NH_3), and volatile organic compounds (VOCs) and provides background science on the contributions of precursors to fine PM formation in Canada. Since these precursors contribute to the formation of PM10, Environment Canada and Health Canada issued a notice of intent in the Canada Gazette in July 2000 to add these four gases to the List of Toxic Substances. **The findings of the precursor report clearly illustrate that further research and monitoring of PM and its precursors is needed to provide guidance on the emission strategies that will work best in regions across Canada to reduce smog and health impacts to Canadians.**

Acid Rain

Acid rain results when sulphur dioxide (SO_2) and oxides of nitrogen (NOx) are released into the atmosphere where they undergo chemical processes to form acids and acidifying sulphates or nitrates. These acidifying compounds can be potentially transported for hundreds of kilometres before falling to the Earth as rain, fog, snow (wet deposition) or as fine particles (dry deposition).

A University of Dalhousie scientist, Dr. Eville Gorham, identified the acid rain issue in Canada as early as 1955. He recorded unusually high acidity levels in lakes and in precipitation in Nova Scotia, and suggested that the cause could be pollution from distant sources. During the 1970s, many countries started noticing changes in fish populations in lakes and damage to certain trees. By the late 1970s,

concerns lead to international efforts to identify the causes and effects of long-range and transboundary transport of air pollutants leading to acid rain.

In 1985, the Eastern Canada Acid Rain Program committed Canada to reduce SO_2 emissions in the seven provinces from Manitoba eastward. By 1994, a 40% reduction from 1980 levels was achieved. In 1998, the provinces, territories and the federal government signed the Canada-Wide Acid Rain Strategy for Post-2000, committing them to further actions to deal with acid rain. **In 1999, the most recent year for which data is available, sulphur dioxide emissions in eastern Canada had been reduced 58% from 1980 levels. (Reductions in the emissions of nitrogen oxides have been much less.) Despite progress in emission reductions, the recovery of natural ecosystems has been much slower than anticipated and acid rain continues to affect lakes, forests, wildlife and health.**

The Science Assessment and Integration Branch's Acid Rain activities include work at both national and international levels in providing science advice and guidance to a full range of policy development activities. **SAIB lead the 1997 Canadian Acid Rain Assessment in support of initiatives under The Canada-Wide Acid Rain Strategy for Post-2000.** SAIB also contributes to the annual progress reports on the Canada-Wide Acid Rain Strategy for Post-2000. Branch science advisors work in concert with stakeholders - including other federal departments, provincial, territorial and municipal governments – and international policy committees (Canada/United States, and United Nations Economic Commission for Europe). The next science assessment on acid rain and its effects has already begun and will be published in 2004.

Climate Change

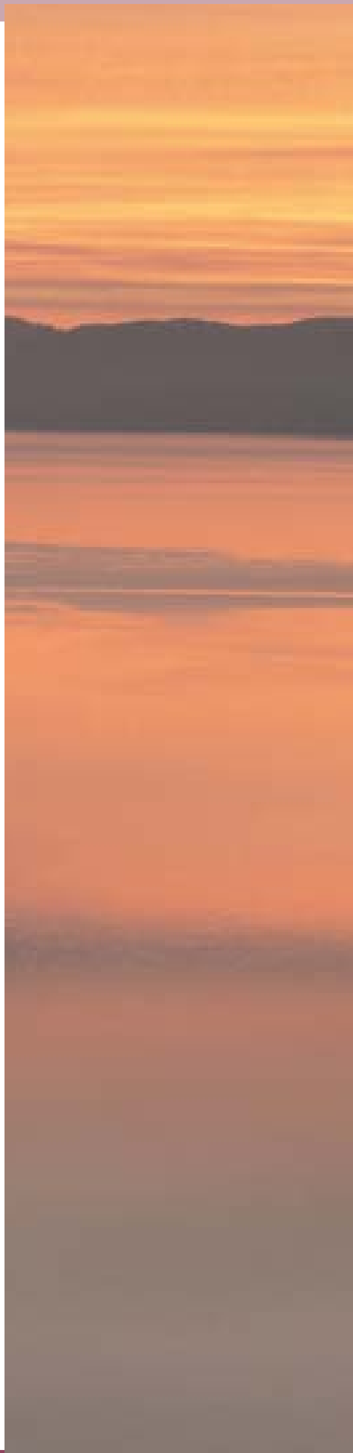
Climate change is a complex, global issue that demands international and interdisciplinary collaboration in research assessment and mitigation.

The greenhouse gases that cause climate change are generally long-lived and well mixed in the atmosphere. Hence, their impacts on climate are relatively independent of the geographical location of their emission sources. Furthermore, the first order impacts of rising greenhouse concentrations are global in scale, which in turn generate second and third order impacts that influence the unique characteristics of national and regional climates. Recognizing the global scale of this issue, The World Meteorological Organization (WMO), United Nations Environmental Program (UNEP) and the International Council for Scientific Unions (ICSU) jointly established a World Climate Program in 1979 to help plan and coordinate a related international research program. Related research involves many scientific disciplines and now results in the publication of several thousand new peer-reviewed scientific papers relevant to climate change each year.

In 1988, the United Nations (UN) General Assembly requested that the WMO and UNEP jointly establish an international assessment process to take periodic stock of progress in climate change science and advise policy makers of the relevance of that science to related policy issues. As a result, the Intergovernmental Panel on Climate Change (IPCC) was established later that year

To date the IPCC has prepared three major science assessments, the first in 1990, the second in 1995 and the third in 2001. IPCC has also prepared and issued a number of other special reports. These reports have provided the scientific basis for the preparation of the Framework Convention on Climate Change (FCCC) - that was approved at the UN Conference on Environment and Development in 1992 - and the related Kyoto Protocol approved by the Conference of the Parties to the FCCC in 1997. Canada has ratified the FCCC and has recently announced its intent to submit its ratification of the Kyoto Protocol to parliamentary vote later this year.

The Science Assessment and Integration Branch's activities relevant to climate change involve science assessment work at both international and national levels. **SAIB science advisors manage the process behind Canada's participation in the IPCC, including the coordination of involvement by Canadian scientists in the preparation and review of IPCC reports.** SAIB also independently undertakes regular reviews of recently published literature and advises the Canadian scientific community, policy community and the general public on the related science. This climate change science is communicated in a variety of ways including through Ministerial briefings, public presentations, and publication of two issues of the **CO_2/Climate Report** (Winter and Spring editions) and a **Climate Change Digest** series.



Stratospheric Ozone Depletion / UV Radiation

Stratospheric ozone depletion results when the natural balance between ozone production and destruction in the stratosphere is disturbed by the presence of such anthropogenic ozone-depleting substances as chlorine and bromine.

A thinning of this protective ozone layer is a concern because it allows increased levels of harmful ultraviolet radiation (UV), with the potential to adversely affect human health and the environment, to reach the earth's surface. International agreements have been established to phase out the production of ozone-depleting substances, which are part of the family of anthropogenic chemicals called CFCs (chlorofluorocarbons).

The United Nations Environment Program (UNEP) established the Co-ordinating Committee on the Ozone Layer (CCOL) in 1977 and adopted the World Plan of Action on the Ozone Layer. In the late 1970s and early 1980s, Canada and the United States banned the non-essential uses of CFCs. In 1985, British scientists first reported the discovery of the 'Antarctic ozone hole' and in 1986, Canadian scientists launched studies of the Arctic ozone layer. The international community came together in Canada in 1987 and the landmark international agreement, The Montreal Protocol on Substances that Deplete the Ozone Layer, was signed by 24 countries, with all parties to the Protocol agreeing to freeze production and consumption of CFCs at 1986 levels. In the first decade since the agreement was signed, nine meetings of the Parties to the Montreal Protocol have been held internationally.

SAIB coordinates the role of Meteorological Service of Canada scientists in international and national science assessments. For Example, SAIB played a coordinating role in the ozone assessments; *A Canadian Perspective on the Changing Ozone Layer (1997);* and *Arctic Ozone: The sensitivity of the ozone layer to chemical depletion and climate change*, and wrote the assessment; *Ozone Depletion and Climate Change: Understanding the Linkages.*

The Branch also provides advice and guidance to UV programs promoting sun protection, through organizations such as The World Health Organization (WHO), The World Meteorological Organization (WMO) and Health Canada. **SAIB launched Environment Canada's UV Index Sun Awareness Program and the Sun Savvy School Club to provide resource material to teachers and students on sun protection.** Branch advisors provide information to Canadians on sun protection through media interviews, and maintain a watch over current stratospheric ozone conditions over Canada, monitoring trends, and informing Canadians.

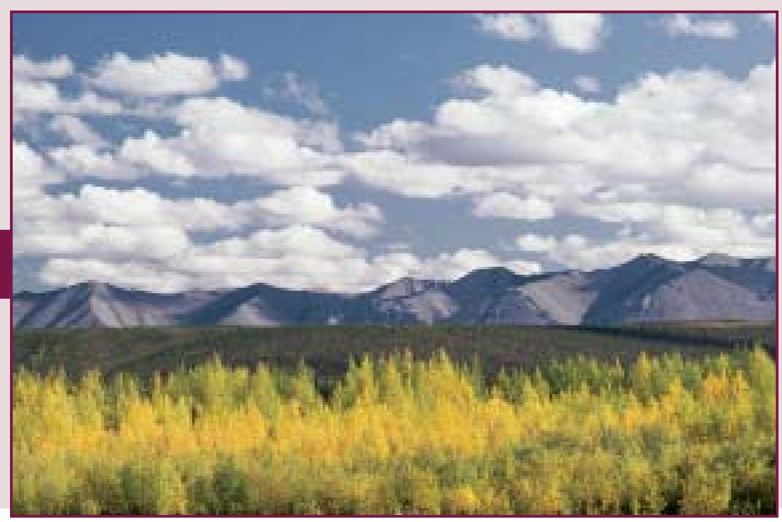
Atmospheric Change and Biodiversity

Climate change, stratospheric ozone depletion, acid rain and smog all have a cumulative impact on the atmosphere, biodiversity, human health and water.

Because all of these issues impact our singular atmosphere, an integrated approach is required to "assess the whole as well as the parts". SAIB science advisors work collectively to study the impacts of these issues on global, national, regional and even local scales, and to understand the linkages between issues. The role of the atmospheric change and biodiversity science advisor is to create linkages among interdisciplinary scientists, stakeholders and policy makers to work towards a more integrated approach to identifying and responding to the impacts of atmospheric change. Branch advisors provide guidance and advice toward the development of policies that are aimed at multiple and cross-issue benefits. SAIB science advisors have worked with many agencies, such as, the Convention on Biological Diversity (CBD), the Intergovernmental Panel on Climate Change (IPCC), UNESCO's Man and the Biosphere and the Smithsonian Institution to enhance the interlinkages between atmospheric issues, biodiversity and human health.Water availability, which is closely linked to climate change and water quality, is becoming an issue of concern in Canada. A science assessment on water availability has already begun and will be published in 2003. SAIB will play a coordinating role in this assessment.

Examples of SAIB integrated assessments include:

1. Biometeorology and Adaptation in the Context of Climate Change and Biodiversity, 2002 (Partner: Commission- International Society of Biometeorology).
2. Integrated Mapping Assessments, 2001 (Partner – University of Toronto).
3. The Relative Magnitude of the Impacts and Effects of GHG-Related Emission Reductions, 1999.
4. Atmospheric Change in Canada: An Integrated Overview, 1999.
5. Decoding Canada's Environmental Past: Adaptation Lessons Based on Changing Trends and Extremes in Climate and Biodiversity, 1999.
6. Decoding Canada's Environmental Past: ClimateVariations and Biodiversity Change during the last Millennium, 1998.
7. Atmospheric Change in Canada: Assessing the Whole as Well as the Parts, 1998.



Adaptation and Impacts Research Group (AIRG)

AIRG was established in 1994 to address issues related to the impact of climate change and to develop adaptation mechanisms. The overall goal of the Group is to make available scientifically sound information on the environmental, social and economic risks and impacts caused by atmospheric change, variability and extremes in climate; and on the viability of adaptive responses. AIRG performs R&D and works closely with universities and other agencies to provide information to the scientific community, policy and decision-makers, and to the general public.

Introduction

Within the impacts and adaptation research community, AIRG provides scientific expertise and leadership. **Staff, many of whom are adjunct professors and graduate student supervisors, are located on the campuses of several Canadian universities and work closely with faculty to further research and publish the results in scientific literature.** Within government, the Group provides expert advice to policy and decision makers by identifying key Canadian interests in research done in Canada, and elsewhere, and presenting and transferring that information to support Canadian decision making processes.

The following paragraphs describe some of the Group's significant accomplishments over the past few years.

Canada Country Study (CCS)

Completed in 1998, this was the first Canadian national assessment of the potential impacts of climate change and variability, including consideration of existing and potential adaptive responses.

The CCS focused on reviewing existing scientific and technical literature to establish Canada's collective understanding of impacts and adaptation options, from national and regional perspectives. The assessment involved researchers and reviewers from government (federal and provincial), universities (across Canada) and the private sector, and drew on Intergovernmental Panel on Climate Change (IPCC) impact assessment technical guidelines.

The CCS was published in eight volumes, six regional, one national and one covering cross-cutting issues, which were supplemented by plain-language documents and a national summary for policy makers. **The *Canada Country Study* is a major reference document that is widely quoted and has had a significant influence on the development of Canada's national implementation strategy.**

Water Basin Impacts and Adaptation Studies

The MacKenzie Basin Impact Study (MBIS)

Several regional case studies have been conducted across Canada – in the MacKenzie Valley, the Great Lakes, and British Columbia. The results of these studies have been published and have been made widely available.

This was a six-year collaborative research effort that culminated in the publication of the *MBIS Final Report* in 1997, along with several refereed journal publications. MBIS broke new ground in that it brought together an integrated regional assessment of climate change impacts with consideration given to multi-stakeholder concerns and to possible adaptation strategies.

The dialogue started by the MBIS has led to other Arctic initiatives, including the establishment of the Northern Climate Exchange at Yukon College in 2000 and the development of other regional case studies in the Bering Sea and Barents Sea regions.

The Great Lakes – St. Lawrence Basin (GLSLB)

This project was a joint Canada-US integrated assessment of the climate change impacts and adaptations using a multi-disciplinary, collaborative framework to link studies on water management, land use, ecosystem health, and human health. The project engaged basin residents in a dialogue on climate change and developed a valuable conceptual framework of adaptation, which has been documented in several special reports as well as in refereed journals.

Regional Case Studies in British Columbia

An impacts and adaptation survey of stakeholders on the Canadian side of the Columbia River Basin was conducted in 1997-98 and was supported by the North American Commission for Environmental Cooperation. Results were combined with work by the University of Washington and the Environmental and Societal Impacts Group of the NCAR (National Center for Atmospheric Research) for a publication on transboundary concerns for the Columbia Basin. A follow-up study on the Okanagan Basin was initiated in May 2000. The objective was to use scenarios of climate and stream flow changes for the Okanagan basin to obtain views from stakeholders on the potential impacts of these scenarios, and on options for adaptation.

Climate Change and Canada's Protected Areas

This AIRG-led study assessed the anticipated impacts of climate change on ecology, heritage and tourism in each of Canada's 38 national parks. This was a significant accomplishment, exceeding the expectations of all participants.

The study's results are providing a basis for integration of climate change considerations into the management plans of several national parks. Subsequent studies have built on this work to identify policy and planning sensitivities and barriers to adaptation. The study received considerable media attention and provided many opportunities, directly and indirectly, for AIRG staff to present the science of climate change impacts and adaptation to a wide range of audiences, including policy makers, and long-range planners and ecologists. As a result of this work, AIRG participated in the foundation of an international research network dedicated to furthering research on climate change and biodiversity conservation, with particular emphasis on the applied implications for protected areas policy and planning.

Natural Weather/Climate Hazards

AIRG is leading the Canadian Natural Hazards Assessment Project (CNHAP), which is designed to provide information for use by Canadian policy and decision makers to develop communities more resilient (impacts less severe and recovery more rapid and productive) to natural hazards and disasters.

The Group is organizing and assembling a set of background papers on Canadian natural hazards and disasters, and editing the volume that will be dedicated to Natural Hazards. The Group will also lead and act as the primary author and editor of a plain language document, in 2003, summarizing the background papers.

Climate and Health

A multi-disciplinary study, led by AIRG, was conducted to assess the implications of climate change on human health, and the actions required for health infrastructure to effectively adapt to these effects in the Toronto-Niagara Region.

An adaptation action plan has been proposed, consisting of five steps: research, improved monitoring and surveillance, education, partnership building, and improved coordinated response.

Adaptations in the Context of Anomalous or Extreme Weather

AIRG has worked with partners from the University of Waterloo, the insurance industry and other government agencies to complete the initial phase of research that examines the transportation sector's sensitivity to climate change, and identifies empirical relationships between weather, collision rates and winter road maintenance (salting).

A recent report discusses the influence of weather information on driver behaviour and examines published estimates of safety benefits associated with winter maintenance. Case studies of specific storms have been completed. Future research efforts will be directed toward predictive models that couple weather and climate forecast products to indices of transportation design and operations at various time scales.

Building Capacity

AIRG has been instrumental in establishing the Canadian Climate Impacts Scenario (CCIS) facility and has organized symposia on communicating climate change.

The CCIS facility provides climate scenarios, related information and tools, and advice. Climate change scenarios have been prepared according to IPCC guidelines for 25 experiments from 6 international modelling centres. The facility is currently preparing scenarios from the CGCM2 experiments. Considerable training in development of scenarios and web-based access to scenarios and related tools has been conducted.

AIRG co-hosted the first international symposium on communicating climate change. The goal of the symposium was to explore effective communication and outreach strategies and their essential role in responding to climate change. Two hundred and seventy delegates from ten countries attended the three days of presentations, displays and communication and outreach workshops. Proceedings totalling over 800 pages were presented.

Intergovernmental Panel on Climate Change (IPCC)

AIRG has participated in various aspects of the IPCC's work. Most recently, the Group acted as the convening lead author for the North American chapter of the Special Report on Regional Impacts of Climate Change, within the IPCC Third Assessment Report (TAR). AIRG had two contributing authors and one review editor on the Working Group II TAR. The Group also participated in the preparation of the recently completed IPCC Synthesis Report.

Acronyms

AAFC	Agriculture and Agri-Food Canada
ACARS	Aircraft Communication Addressing and Reporting System
ACE	Arctic Cloud Experiment
ACE	Aerosol Characterization Experiment
ACIA	Arctic Climate Impact Assessment (ACIA)
ACSD	Atmospheric and Climate Science Directorate
ACSYS	Arctic Climate System Study
ADOM	Acid Deposition and Oxidant Model
AEPD	Atmospheric Environmental Prediction Directorate
AEROCAN	Aerosol Canada
AERPI	Atlantic Environmental Prediction Research Initiative
AGCM	Atmospheric General Circulation Model
AIRA	Aircraft Icing Research Alliance
AIRS	Alliance Icing Research Study
AIV	Aviation Impact Variable
ALSM	AES Lagrangian Sulphur Model
AMDAR	Aircraft Meteorological Data Relay
AMIP	Atmospheric Model Intercomparison Project
AMSU-A	Advance Microwave Sounding Unit - A
AMWSD	Atmospheric Monitoring and Water Survey Directorate
AQ	Air Quality
AQPP	Air Quality Prediction Program
AQRB	Air Quality Research Branch
ARCAD	Analyse de résultats de cycles d'Assimilation des données
ARMA	Data Assimilation and Satellite Meteorology Division
ARMP	Cloud Physics Research Division
ARQI	Modelling and Integration Research Division
ARQM	Systematic Measurements and Data Analysis Division
ARQP	Processes Research Division
ARQX	Experimental Studies Division
AURAMS	A Unified Regional Air Quality Modelling System
AVHRR	Advance Very High Resolution Radiometer
AVISA	Airport Vicinity Icing and Snow Advisor
BALTEX	Baltic Sea Experiment
BASE	Beaufort and Arctic Storms Experiment
BERMS	Boreal Ecosystem Research and Monitoring Sites
BrO	Bromine Oxide
BrOx	Oxides of Bromine
BSRN	Baseline Surface Radiation Network

CAM	Canadian Aerosol Module
CAMNet	Canadian Atmospheric Mercury Monitoring Network
CANFIS	Co-active Neuro-fuzzy Inference System
CANSIS	Canadian Soil Information System
CAPMoN	Canadian Air and Precipitation Monitoring Network
CARBOEUROPE	A cluster of projects to understand and quantify the carbon balance of Europe
CART	Classification And Regression Trees
CASP	Canadian Atlantic Storms Program
CCA	Canonical Correlation Analysis
CCAF	Climate Change Action Fund
CCCma	Climate Modelling and Analysis Division
CCIN	Canadian Cryosphere Information Network
CCME	Canadian Council of Ministers
CCOL	Coordinating Committee on the Ozone Layer
CCRM	Climate Monitoring and Data Interpretation Division
CCRN	Canadian Climate Research Network
CCRP	Climate Processes and Earth Observation Division
CCRS	Canadian Centre for Remote Sensing
CCS	Canada Country Study
CE	Clean Environment
CEC	Commission for Environmental Cooperation
CEPA	Canadian Environmental Protection Act
CEPS	Canadian Emissions Processing System
CET	Clean Environment Table
CFCAS	Canadian Foundation for Climate and Atmospheric Science
CFCs	Chloro-fluorocarbons
CFDE	Canadian Freezing Drizzle Experiment
CFS	Canadian Forestry Service
CGCM	Coupled Global Coupled Model
CHIPS	Canadian Hydrometeorological Information and Predictions System
CHRONOS	Canadian Hemispheric and Regional Ozone and NO_x System
CICS	Canadian Institute for Climate Studies
CLASS	Canadian Land Surface Scheme
CliC	Climate and Cryosphere project
CliC NEG	CliC Numerical Experimentation Group
CLIVAR	Climate Variability and Predictability
CMAM	Canadian Middle Atmosphere Model
CMAM-DA	CMAM Data Assimilation
CMC	Canadian Meteorological Centre
CMIP	Coupled Model Intercomparison Project
CNHAP	Canadian Natural Hazards Assessment Project
CNR	Climate Research Network
CO_2	Carbon Dioxide
COADS	Comprehensive Ocean-Atmosphere Data Set
COMET	US National Weather Service Cooperative Operational Meteorological Training Program
COMM	Communauté pour la modelisation meso-echelle
CRB	Climate Research Branch
CRCM	Canadian Regional Climate Model
CRN	Climate Research Network

CRYSYS	Cryosphere System to monitor global change in Canada
CSA	Canadian Space Agency
CSE	Continental Scale Experiment
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSM	Climate System Model
CTVB	Climate Trends and Variations Bulletin
CWRP	Canadian Weather Research Project
CWS	Canada-wide Standards
DASM	Data Assimilation and Satellite Meteorology Division
DES	Data Exchange Standard
DFO	Department of Fisheries and Oceans
DGO	Director General's Office
DMS	Dimethyl sulphide
DND	Department of National Defence
EC	Environment Canada
ECE	Economic Commission for Europe
ECHAM	An ECMWF forecast model modified by the Hamburg climate modelling group at the Max Planck Institute for Meteorology
ECMWF	European Centre for Medium-range Weather Forecasts
ECS	Environmental Conservation Service of Environment Canada
ELBOW	Effects of Lake Breezes On Weather
EMAN	Ecological Monitoring and Assessment Network
EnKF	Ensemble Kalman Filter
ENSO	El Nino-Southern Oscillation
EOS	Earth Observing System
EPS	Environmental Protection Service of Environment Canada
EPS	Ensemble Prediction System
ERAF	Environmental Research Aircraft Facility
ESA	European Space Agency
FAA	Federal Aviation Administration
FCCC	Framework Convention on Climate Change
FIRE-ACE	First ISCCP Regional Experiment – Arctic Cloud Experiment
FPA	Forecast Production Assistant
G&C	Grants & Contributions
GAME	GEWEX Asian Monsoon Experiment
GAW	Global Atmosphere Watch Program
GC3M	Global Coupled Carbon Climate Model
GC-C-IRMS	Gas Chromatography Combustion Isotope Ratio Mass Spectrometry
GCIP	GEWEX Continental Scale International Project
GCM	Global Climate Model
GCOS	Global Climate Observing System
GDAS	Global Data Assimilation System
GEM	Global Environmental Multi-scale
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory
GLSLB	Great Lakes – St. Lawrence Basin
GLWQA	Great Lakes Water Quality Agreement
GOES	Geostationary Operational Environmental Satellite
GOOS	Global Ocean Observing System

GPS	Global Positioning System
GRAHM	Global and Regional Atmospheric Heavy Metals
GSN	GCOS Surface Network
GTOPO	Global Topographic Data with a horizontal spacing of 30 arc seconds
HadCM	Hadley Centre Coupled Model
HAPS	Hazardous Air Pollutants
HC	Health Canada
HCH	Hexachlorocyclohexane
HIMAP	High Resolution Model Application Project
HIRS	High Resolution Infrared Sounder
IADN	Integrated Atmospheric Deposition Network
IJC	International Joint Council
IOS	Institute of Ocean Sciences
IPCC	Intergovernmental Panel on Climate Change
ISBA	Interactions Soil-Biosphere-Atmosphere
ISCCP	International Satellite Cloud Climatology Project
ITWG	International TOVS Working Group
JCOMM	Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology
KARDS	King Automated Radar Display System
LBL	Line By Line
LFV	Lower Fraser Valley
LIDAR	Light Detection and Ranging
LITE	LIDAR In-space Technology Experiment
LRTAP	Long Range Transport of Air Pollutants
LUTE	Laboratoire Universitaire sur le temps extreme
LWOM	Living Within Our Means
MAESTRO	Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved from Occultation
MAGS	Mackenzie GEWEX Study
MAM	Middle Atmosphere Model
MANTRA	Middle Atmosphere Nitrogen Trend Assessment
MAP	Management, Administration and Policy
MAP	Mesoscale Alpine Programme
MATCH	Model for Atmospheric Chemistry and Transport
MBIS	MacKenzie Basin Impact Study
MEDIA	Multi-compartment Environmental Diagnosis and Assessment
MERMOZ	Montreal Experiment on Regional Mixing and Ozone
MITE	Metals in the Environment
MOC2	Modelling of Climate and Clouds
MOM	Modular Ocean Model
MOS	Model Output Statistics
MRB	Meteorological Research Branch
MSC	Meteorological Service of Canada
NADP/NTN	National Atmospheric Deposition Program/National Trends Network
NAO	North Atlantic Oscillation
NARCM	Northern Aerosol Regional Climate Model
NARE	North Atlantic Research Experiment

NARSTO	North American Research Strategy on Tropospheric Ozone
NASA	National Aeronautics and Space Administration
NAtChem	National Atmospheric Chemistry Database and Analysis Facility
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NCOM	NCAR CSM Ocean Model
NDSC	Network for Detection of Stratospheric Change
NESDIS	National Environmental Satellite, Data and Information Service
NEXRAD	Next Generation Weather Radar System
NFIS	Neuro-Fuzzy Inference System
NMC	National Meteorological Center
NOAA	National Oceanographic and Atmospheric Administration
NRC	National Research Council
NRCAN	Natural Resources Canada
NRP	National Radar Project
NSERC	Natural Sciences and Engineering Research Council of Canada
NSIDC	National Snow and Ice Data Center
NSSL	National Sever Storms Laboratory
NWP	Numerical Weather Prediction
O&M	Operating & Maintenance
OGD	Other Government Departments
OI	Optimum Interpolation
OOPC	The Ocean Observations Panel for Climate
PAHs	Polycyclic Aromatic Hydrocarbons
PAN	Peroxyacetylnitrate
PBT	Persistent, bioaccumulative toxic substances
PCBs	Polychlorinated biphenyls
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PDFs	Post-Doctorate Fellowships
PDO	Pacific Decadal Oscillation
PDSI	Palmer Drought Severity Index
PERD	Program for Energy Research and Development
PILPS	Project for Intercomparison of Landsurface Parameterization Schemes
PM	Particulate Matter
PNA	Pacific North American
POP's	Persistent Organic Pollutants
POSS	Precipitation Occurrence Sensing System
ppm	parts per million
PRF	Pulse Repetition Frequency
QPE	Quantitative Precipitation Estimation
R & D	Research and Development
RACE	Radiation, Aerosol and Cloud Experiment
RDAS	Regional Data Assimilation System
RDMQ™	Research Data Management and Quality Control Software System
RFE	Regional Finite Elements
ROC	Relative Operating Characteristic
RPN	Recherche en prévision numérique
S & T	Science and Technology

SAIB	Science Assessment and Integration Branch
SAR	Synthetic Aperture Radar
SFE	Spectral Finite Element
SIMIP	Sea-Ice Model Intercomparison Project
SMIP	Seasonal Model Intercomparison Project
SMR	Soil Moisture Radiometer
SPARC	Stratospheric Processes and their Role in Climate
SSG	Scientific Steering Group
SSM/I	Special Sensor Microwave/Imager
SSMIS	Special Sensor Microwave Imager Sounder
SSPFF	Simulation of Severe Precipitation and Flood Forecasting
SST	Sea Surface Temperature
SWE	Snow Water Equivalent
TAR	Third Assessment Report
TC	Transport Canada
THORPEX	The Observing System Research and Predictability Experiment
TLM	Tangent Linear Model
TOMS	Total Ozone Mapping Spectrometer
TOVS	TIROS Operational Vertical Sounder
UBC	University of British Columbia
UKMO	United Kingdom Met Office
UMOS	Updateable Model Output Statistics
UN	United Nations
UN-ECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UQAM	Université du Québec à Montréal
URP	Unified Radar Processor
USGS	United States Geological Survey
UV	Ultraviolet
VAD	Velocity Azimuth Display
VOCs	Volatile Organic Compounds
VPDB	Vienna Pee Dee Belemnite
WCRP	World Climate Research Program
WEP	Weather and Environmental Predictions
WGSIP	Working Group on Seasonal to Interannual Prediction
WHO	World Health Organization
WMO	World Meteorological Organization
WOUDC	World Ozone and UV Data Centre
WWRP	World Weather Research Program

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