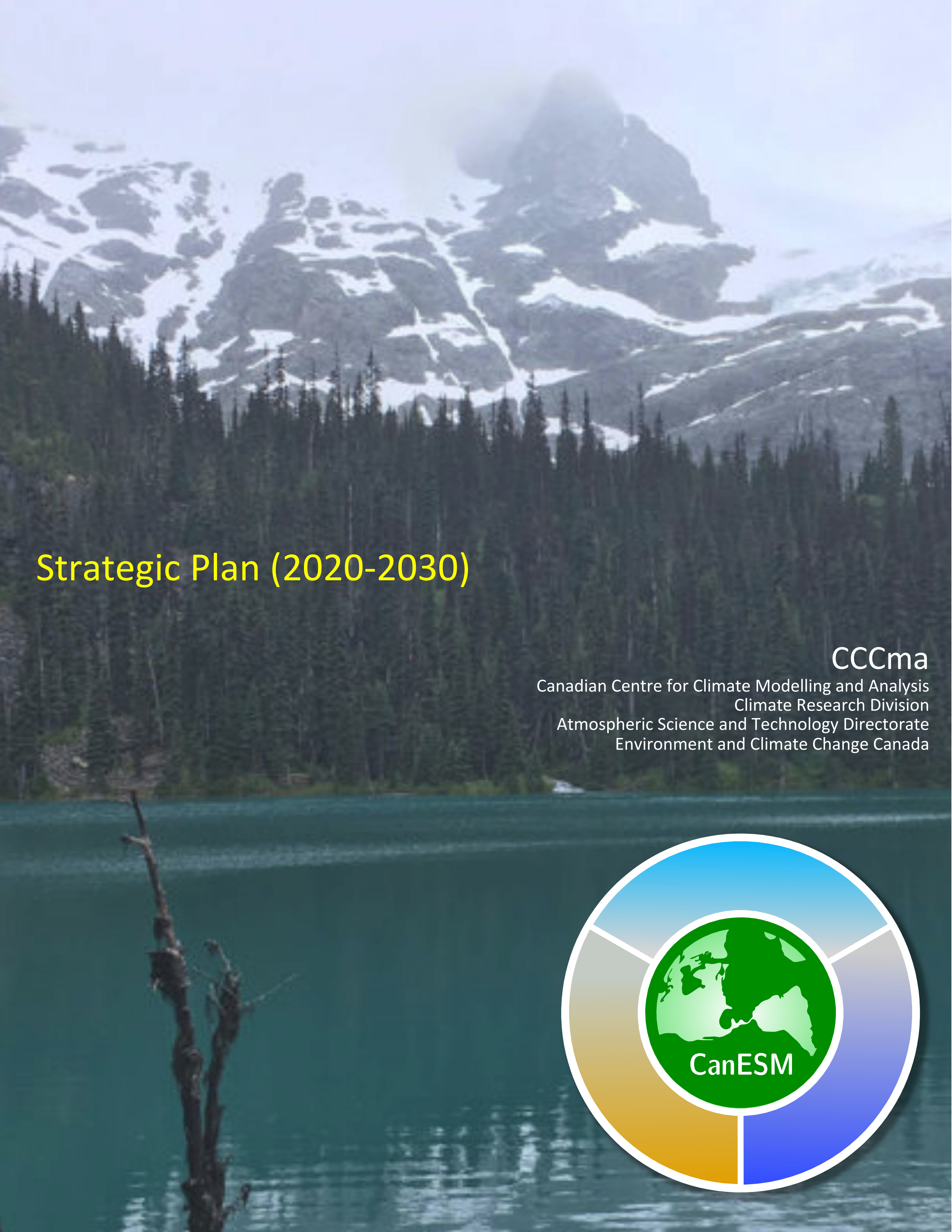


Strategic Plan (2020-2030)

CCCma

Canadian Centre for Climate Modelling and Analysis

Climate Research Division

Atmospheric Science and Technology Directorate

Environment and Climate Change Canada

CanESM

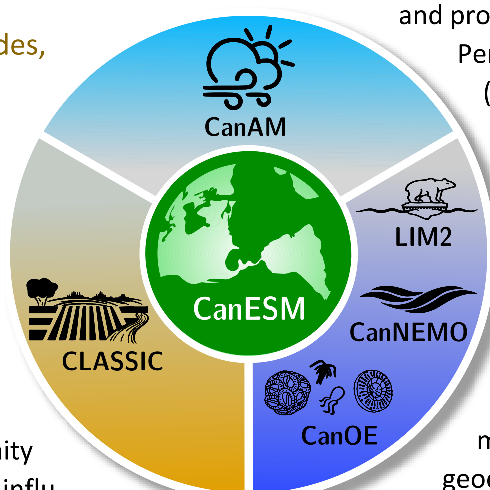
Executive Summary

Vision To serve as the national focal point for global-, continental- and regional-scale climate change projections, analyses, and scientific information for Canadians.

Mission To provide robust climate predictions on seasonal to decadal timescales and climate projections on centennial timescales over Canada and the globe through the continuous development and innovative application of Canada's suite of global and regional climate (Earth system) models and the expert analysis of their output. The Canadian Centre for Climate Modelling and Analysis (CCCma) is a world-leading centre for the development and application of Earth system models addressing key emerging scientific questions that provide timely, relevant knowledge and information to Canadians and others striving to mitigate and adapt to climate change. Our work responds to the growing need for climate information by those engaged in domestic and global efforts to combat climate change and manage the associated risks. In addition, this research fulfills Canada's international commitments to promote further scientific understanding of climate change and to exchange climate information.

Impact Over the past four decades, CCCma has developed a state-of-the-science, global-scale, climate modelling capability and is the sole Canadian provider of comprehensive Earth system modelling capacity. Our scientific leadership in the field of Earth system modelling means that the Climate Research Division's (CRD's) research scientists are an integral part of the international research community spearheading ongoing developments, influencing international science research strategies, and acting as ambassadors for Canadian climate science. Such deep international connections allow our scientists to integrate scientific and technological advances of the international community into Canada's model development, applications and analysis efforts, thereby improving the quality and robustness of climate information products. The development of such expertise within the Canadian government means that Canadian decision-makers have the highest level of expert scientific advice available to them to support policy and regulatory deliberations, decisions and actions related to climate change.

Capacity The Climate Research Division leads the development and application of a tightly integrated suite of models designed to realistically simulate the Earth system, to make initialized climate predictions and forced climate projections, and to provide high-resolution downscaling of global results to the regional level to support a range of climate impact assessment outcomes. The ongoing development of Canada's modelling system underpins many of the Climate Research Division's key climate research activities. At the heart of the integrated modelling system is the global, fully coupled Canadian Earth System Model (CanESM), and the information technology (IT) infrastructure used to execute the model and process its output on High Performance Computer (HPC) systems. CanESM is comprised of an atmospheric model, CanAM; land surface and terrestrial ecosystem model, CLASSIC; ocean model, CanNEMO; sea-ice model, LIM2; and biogeochemistry ocean ecosystem model, CanOE. The current version of CanESM represents the culmination of



several decades of active research involving collaborators within the Climate Research Division, the Atmospheric Science and Technology Directorate, other government departments (notably Fisheries and Oceans Canada), and the academic community. Built around CanESM is a family of model components that initialize climate predictions for seasonal to decadal forecasts, enable regional downscaling, and support a range of climate process studies.

Challenges

As the consequences of human-induced climate change become increasingly evident, the Earth system modelling community is being called upon to answer more diverse science-policy questions with greater specificity. Meeting this urgent need requires physical processes to be modelled more realistically and in ever-increasing detail. The concomitant increase in model complexity necessitates improved model efficiency and enhanced scientific capacity.

Continued development and maintenance of Canada's Earth system model presents two key scientific challenges for the program. The first is maintaining a state-of-the-science representation of the climate system, which requires continuous development of existing model components and the introduction of representations of new processes that are important to understanding environmental changes relevant to adaptation and mitigation. The second is modernizing the existing model code to take full advantage of new high performance computing systems that will be installed and are essential to running efficient simulations.

Goals

Based on the success of our Earth System modelling program, the expertise it has accrued, our on-going engagement with the larger climate and atmospheric research community, and our role as a convener of Canadian Earth system science, CanESM is well positioned to be the foundation of a comprehensive integrated modelling infrastructure within the Canadian community. With components that are adapted to interface with downstream modelling systems (e.g., biodiversity models, human health risk assessment models, highly resolved hydrological models), CanESM can provide the highest-quality of climate change information so that Canadian decision makers can adequately respond to the diverse and growing information needs of Canadian society.

Opportunity

The need to sustain Canada's state-of-the-science Earth system model underpins many of the information requirements identified by Canadian decision-makers and stakeholders in *Climate Science 2050: Advancing Science and Knowledge on Climate Change* (CS2050). These requirements include the advancement of our understanding of how weather and climate extremes are projected to change in a changing climate; the role of terrestrial and marine carbon cycle processes and feedbacks on the climate system; the potential for carbon sink enhancement; and the sensitivity of carbon stocks to climate warming, particularly in the Arctic. CS2050 also identifies the need for Earth system science to support mitigation including the climate response and co-benefits of reducing emissions of short-lived climate forcers and for developing insight into the climate response and potential unintended consequences of climate engineering. The CS2050 science priorities of developing more skillful climate predictions on near-term time scales and of further developing climate projection downscaling techniques are directly responsive to the information requirements of adaptation programs.

Planning

During the strategic planning process for CRD's Canadian Centre for Climate Modelling and Analysis, seven scientific priorities were identified to ensure that CanESM remains well positioned to respond to the evolving climate information needs of Canadians. These scientific priorities address the two key scientific challenges for the program and align with the priorities identified by Canadian decision-makers and stakeholders in CS2050. These priorities necessitate that the Government of Canada continues to invest in Canada's core strength of developing and maintaining Canada's state-of-the-science Earth system model and in the application of the model to advance actionable science aligned with CS2050 priorities.

The first priority (1) addresses the two key scientific challenges of the program, namely, the maintenance and development of a state-of-the-science representation of the climate system; and, modernizing the existing model code to take full advantage of new high performance computing systems. The first priority also recognizes that a high-quality global model is the necessary starting point for subsequent downscaling which uses a regional climate model to provide more spatial detail over Canada as needed by users from a range of disciplines. Priorities two (2) to seven (7) address the priority needs of Canadian society for climate change projections as described in CS2050, namely, science to support the achievement of carbon neutrality in Canada, and to build healthy and resilient communities and ecosystems.

Priority Area Action Plan

1 **The Changing Earth System – Past and future:** We will modernize the existing CanESM code, further develop existing model components, and introduce representations of new processes to advance our fundamental understanding of the Earth system and improve simulations of the response of this system to changes in human and natural drivers.

2 **Detailed Regional Climate Information for Canadian Decision Makers:** In order to respond to the increasing demands for higher resolution projections of climate change, we will continue to further develop the Canadian Regional Climate Model (CanRCM) which takes global model output and refines it to include enhanced representation of the terrestrial ecosystem and regional topographical features (such as the Great Lakes and Rocky Mountains). We will also add new regional ocean modelling capabilities to CanESM to provide consistent, high resolution, ocean and sea-ice projections for Canada's three oceans. Our regional Earth system model, based on the coupling of the CanRCM to the Canada's Three Ocean's Downscaling System (CanTODS) will provide seasonal predictions for both atmospheric and ocean variables.

3 **Carbon Cycle Earth System Feedbacks:** We will advance our understanding of the role of biogeochemical feedbacks in the Earth system and will better quantify the sensitivity of the climate system, including Arctic ecosystems, to anthropogenic carbon emissions by improving the representation of terrestrial and marine ecosystem and carbon cycle components in the CanESM framework.

4 **Seasonal to Decadal (S2D) Climate Prediction:** We will improve Canada's seasonal to decadal (S2D) prediction system and expand the number of climate metrics forecasted by this system to allow development of products tailored to specific sectors, and eventually individual users.

5 **Climate Extremes and Extreme Event Attribution:** We will provide timely and credible information on the role of anthropogenic climate change in high impact climate events and on future changes in climate extremes in Canada to support climate risk management by developing a system suitable for transfer to operations for extreme event attribution.

6 **Role of Short-lived Climate Forcers:** We will provide improved estimates of the climate and air quality co-benefits of mitigation of short-lived climate forcers by improving representation of aerosols and chemistry in CanESM.

7 **Implications of Climate Engineering and Response to Mitigation Options:** We will analyse the potential global, regional and Canadian climate impacts of solar radiation management (SRM) and carbon dioxide removal (CDR) scenarios by simulating and analysing climate impacts of SRM, CDR and other mitigation options.

Requirements

To realize the goals of this plan, the following actions are required:

1) ***Sustained investments in key technical and scientific human resource capacity within the Climate Research Division.*** The nature of these investments has been defined through a human resources challenge function that was part of the process to develop the strategic plan;

2) ***Enhanced external collaborations to further the development and analysis of CanESM as the foundation of a comprehensive integrated modelling system, with components that are designed to support downstream modelling systems (e.g., climate impact models).*** This will be achieved by first developing the model in a manner that lowers the technical barriers to using the model for partner organizations and the academic community; followed by developing a clear governance framework to support an expansion in the scope of collaboration ; and

3) ***The establishment of a standard modelling framework and shared coding standards to support effective collaborations with partner organizations.***

Summary

As a northern nation, Canada has experienced a rate of environmental change more pronounced than that of many nations, which has had significant and wide-ranging impacts on almost every facet of our society, economy and infra-structure. We know that this will continue into the future. This summary highlights the scientific priorities for Canada's Earth system modelling research program. Research and development focused on these priorities are required to deliver timely, relevant knowledge and information to Canadians and others striving to mitigate and adapt to climate change over the next decade. These priorities, and the accompanying implementation plan, build on CRD's strong scientific leadership and foundational capacity in this scientific domain and leverage the scientific computing and monitoring technology advances of the past decade to enable Environment and Climate Change Canada to maximize its contribution to informing responses to Canada's current adaptation and mitigation challenges.

Canadian Centre for Climate Modelling and Analysis (CCCma) Strategic Plan: 2020 – 2030

Vision Statement

The vision of the Climate Research Division's Canadian Centre for Climate Modelling and Analysis (CCCma) is to serve as the national focal point for global-, continental- and regional-scale climate climate change projections, analyses, and scientific information for Canadians.

Mission Statement

CCCma's mission is to provide robust climate predictions on seasonal to decadal timescales and climate projections to centennial timescales for both Canada and the globe. This information is used to understand climatic trends and changes in extreme weather and climatic events. Our work informs climate impact and risk analysis, adaptation and mitigation policy- and decision-making, and fulfills Canada's international commitments to increase our understanding of climate change.

CCCma's work responds to the growing need for climate information by those engaged in domestic and global efforts to combat climate change and those focused on managing the risks of climate change in Canada.

CCCma delivers on this mission via continuous development, analysis and application of its global and regional climate (Earth system) models and associated tools.

About the Canadian Centre for Climate Modelling and Analysis (CCCma)

CCCma has developed state-of-the-science, global-scale, climate modelling capacity over the past four decades and is the only research centre in Canada with this capacity. CCCma is embedded within an integrated climate research environment at Environment and Climate Change Canada (ECCC), generating and sharing state-of-the-science knowledge of the climate/Earth system and its evolution in response to human and natural influences. While CCCma has led this modelling endeavour, collaborations with experts in other parts of ECCC, and with other federal government departments and Canadian universities have contributed to the success of this program. Our scientific leadership in the field of Earth system modelling means that CCCma research scientists have been an integral part of the international research community spearheading ongoing developments, influencing international science research strategies, and acting as ambassadors for Canadian climate science. In turn, CCCma scientists have been able to reintegrate scientific and technological advances of the international community into its model development, applications and analysis. Having this expertise within the Canadian government has also meant that Canadian decision-makers have had expert advice readily at hand to support deliberations on climate change policy and action.

CCCma is embedded within an integrated climate research program at Environment and Climate Change Canada. As shown in Figure 1, CCCma is one of five sections within the department's Climate Research Division (CRD). CRD carries out integrated, end-to-end research in which observations, process studies, model development and application, and analysis and diagnostics are used to understand the Earth system and to make quantitative predictions/projections across a range of time and space scales. CRD is

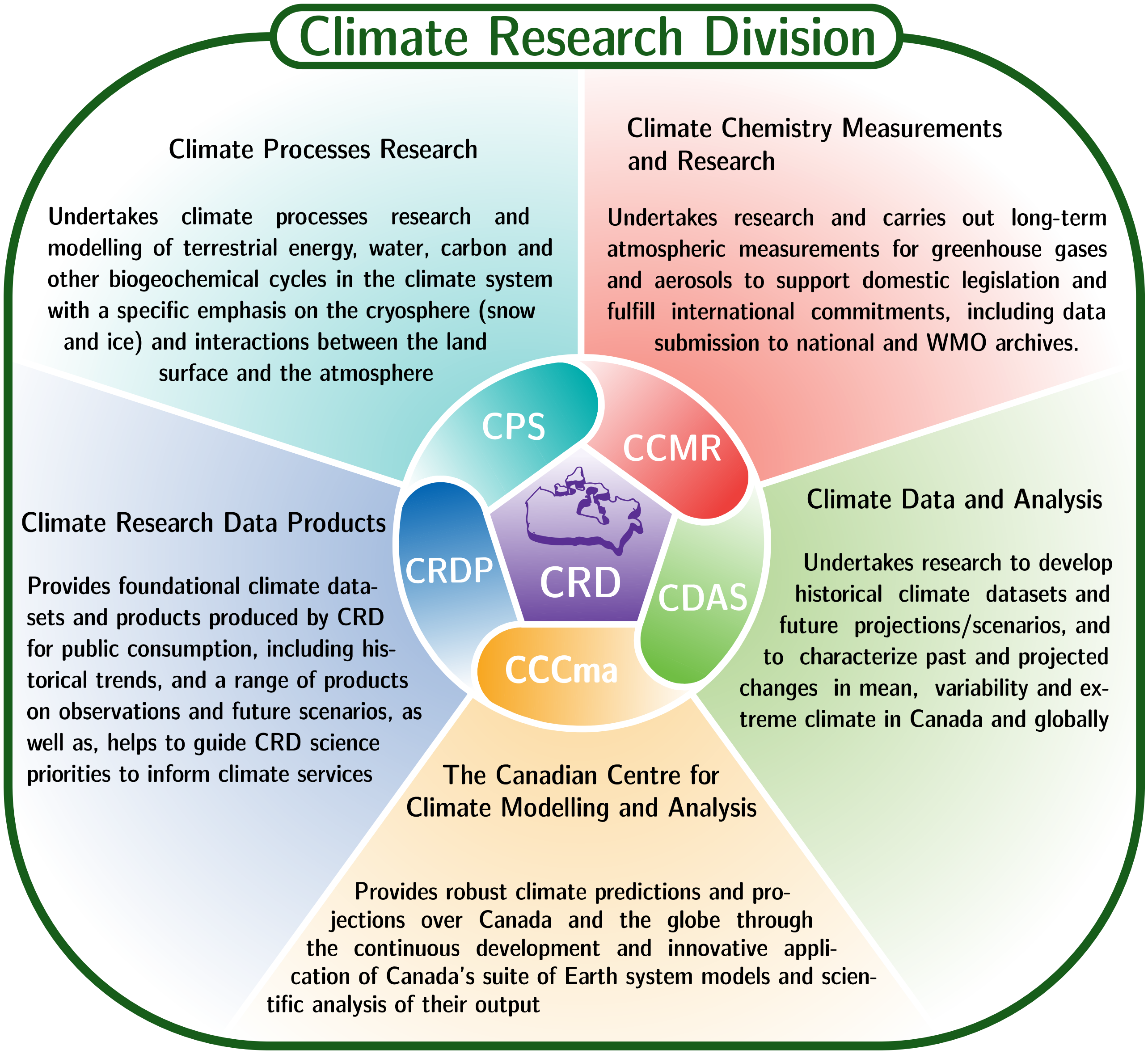


Figure 1. Organizational chart of Environment and Climate Change Canada's Climate Research Division

one of three divisions within the Atmospheric Science and Technology Directorate (ASTD) of Environment and Climate Change Canada, along with the Meteorological Research Division (MRD) and the Air Quality Research Division (AQRD). Collaboration across the three research divisions is fundamental to the Directorate's commitment to provide an integrated research program and is important to delivering on CCCma's mission. As the Earth system modelling community is called upon to answer more diverse science-policy questions with greater specificity, model development and analysis is becoming more complex. The research community is increasingly moving toward a "unified modelling framework" that facilitates the integration of model components developed by different research groups within and outside of government.

The Earth's climate system – or simply, the Earth system - is a complex, integrated system comprising the atmosphere, land, ocean and freshwater (both frozen and liquid), and living things, and the myriad of interactions (e.g., flows of energy, water, carbon and other compounds) between these components. CCCma develops and applies a tightly integrated modelling system in order to realistically simulate the Earth system. The ongoing development of this integrated modelling system underpins our key climate research activities. At the heart of the integrated modelling system is the global, fully coupled Canadian Earth System Model (CanESM), and the software infrastructure used to run the model and prepare model output on High Performance Computing (HPC) systems. CanESM is comprised of an atmospheric model, a land surface and terrestrial ecosystem model, and an ocean model with sea-ice and biogeochemistry embedded (Figure 2). CanESM is, however, more than the sum of its parts. Constructing a global, coupled ESM is a complex undertaking due to feedbacks across components of the system and, thus, requires careful planning, validation, and tuning. Hence, a significant and dedicated effort is required to produce CanESM from its component models.

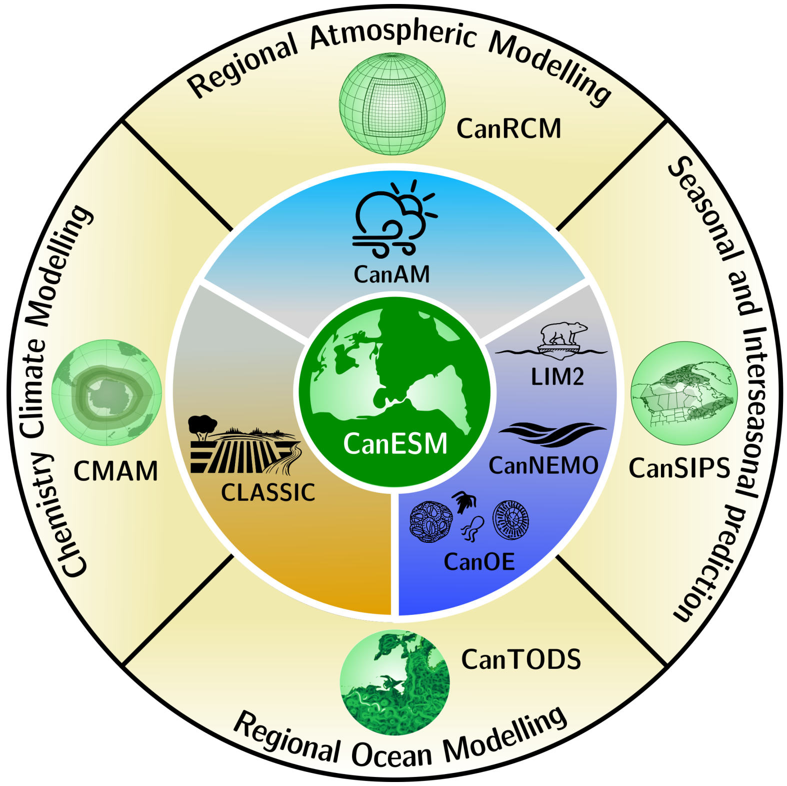


Figure 2. Canadian Earth System Model, core components and modelling systems

Earth system modelling is a multi-disciplinary, international endeavour that involves CCCma collaborations with academic partners, researchers in other parts of ECCC and other government departments, and colleagues in research institutes from around the world. Over the years, the number of organizations that have developed Earth system models has grown considerably from just a few to several dozen. However, a number of these groups use atmosphere, land, and ocean sub-models from other groups, given the huge effort required to develop these models. This limits the diversity of models contributing to coordinated international climate modelling experiments and, in turn, reduces the capacity to quantify uncertainty across models (i.e., fewer unique models means less diversity in model ensembles and, thus, a higher risk of underestimating the uncertainty in model projections). Because most components of CanESM (i.e., atmosphere, land, ocean biogeochemistry) are developed in-house, CanESM makes an important contribution to Earth system model diversity. The application and evaluation of Earth system models are largely done under the auspices of the international Coupled Model Intercomparison Project (CMIP) – a project of the World Climate Research Programme (WCRP) – through which experimental design and model simulations are carefully coordinated so that results from different models can be compared in a scientifically robust manner. CCCma's participation in international model intercomparisons ensures

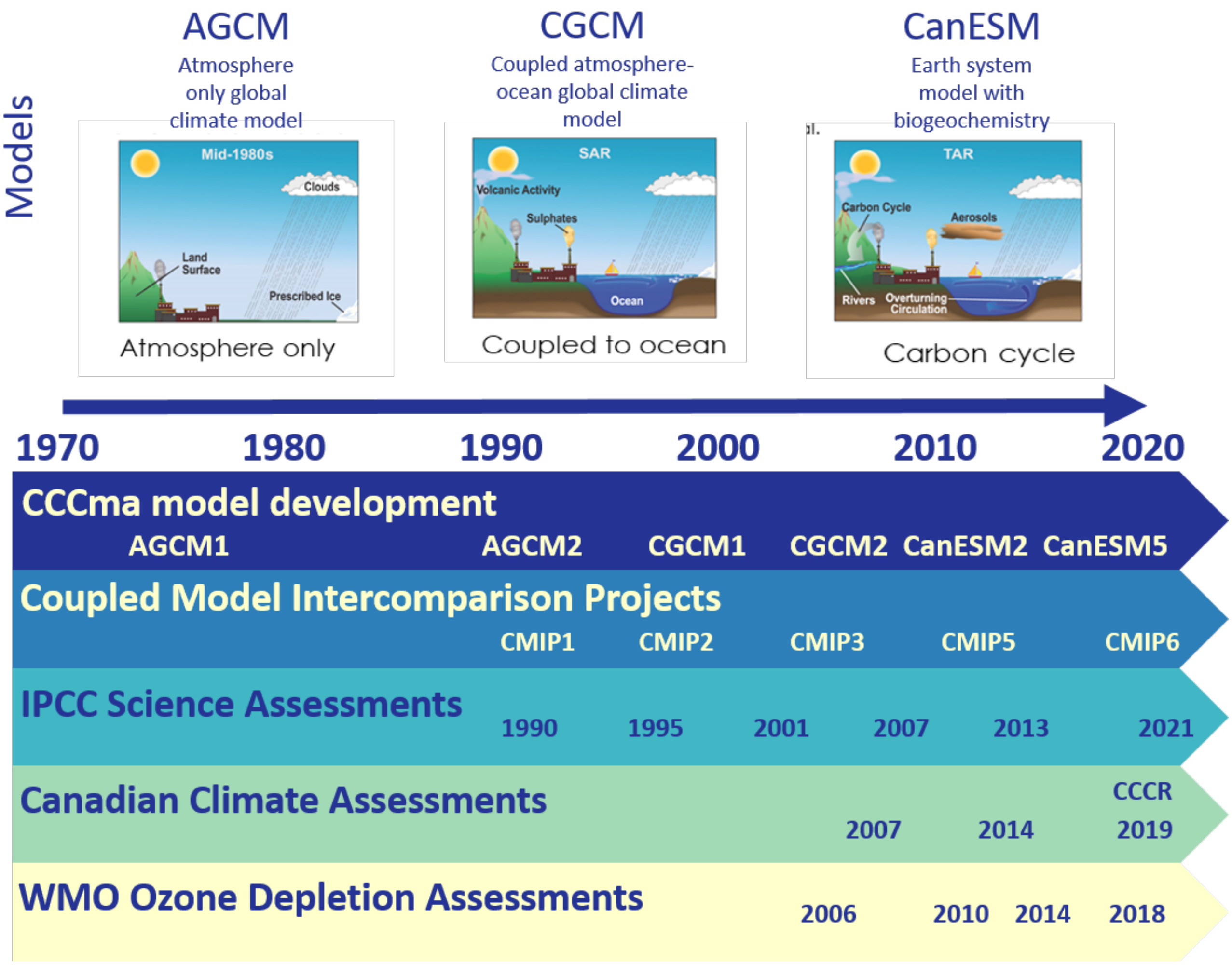


Figure 3. Timeline of CCCma modelling evolution and major science assessments

that CanESM is vigorously tested and drives improvements to its various components, ultimately providing higher confidence in its application to address science and policy questions.

The CCCma modelling system produces model simulations and other data products that fulfill international research obligations and serve international climate science projects and assessments including the CMIP (Figure 3). As a Party to the United Nations Framework Convention on Climate Change (UNFCCC), Canada has a commitment to carry out research to improve understanding of climate change and reduce uncertainties in climate change projections. Similarly, as a Party to the Vienna Convention for the Protection of the Ozone Layer, Canada is committed to carrying out research on ozone depletion and linkages between climate change and ozone depletion. Furthermore, as a northern country and member of Arctic Council, Canada has a commitment to help advance research and knowledge of Arctic environmental change, especially in light of the rapid rate of Arctic warming which is already posing challenges to Arctic communities. In all these fora, state-of-the-science assessments are the central means by which the science community conveys advances in knowledge and understanding to governments

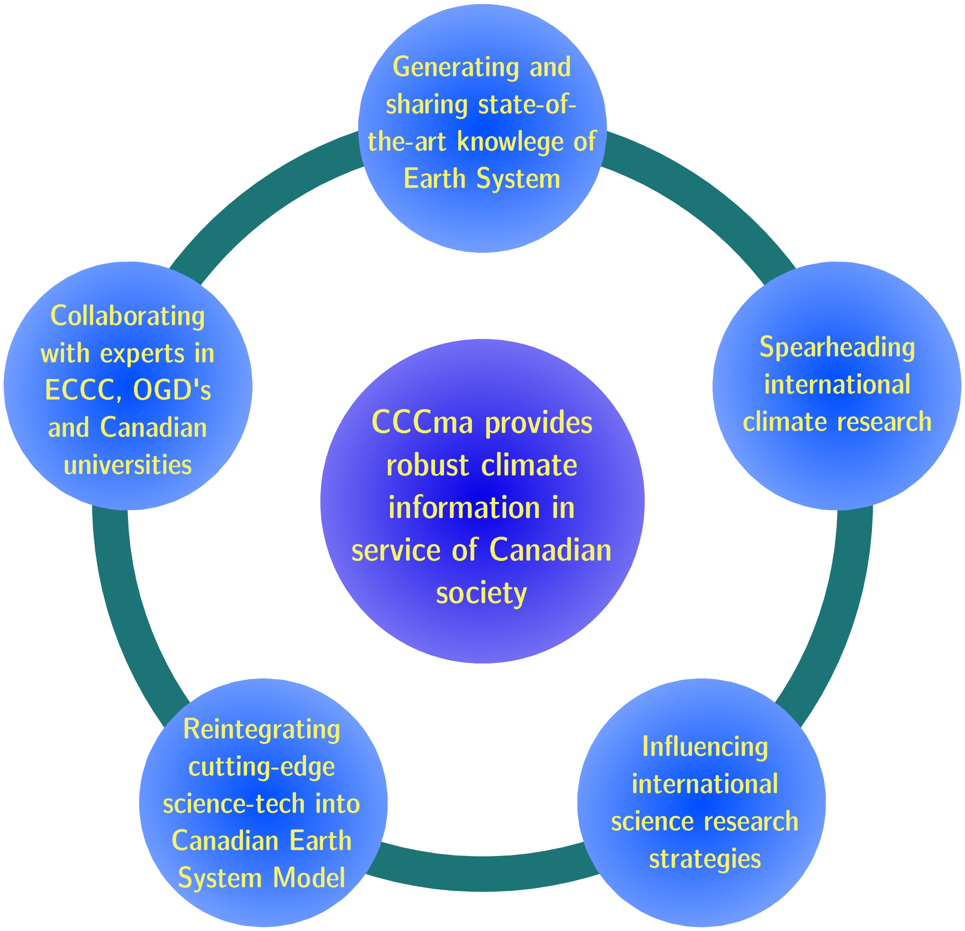


Figure 4. CCCma plays a key role providing robust climate information in service of Canadian society while fulfilling Canada's international obligations, ensuring that Canadian research results are included in international assessments, collaborating with internal and external partners, and providing state-of-science input to national assessments

to inform their ongoing responses to these critical environmental challenges. CCCma plays a key role in providing the climate model simulations, research and assessment contributions to fulfill Canada's international obligations in these areas. Our participation in these activities also helps ensure that Canadian research results are included in international assessments (Figure 4).

Within Canada, the national climate change assessment process is a vital means of conveying the state of knowledge about climate change in Canada, and its consequences, to Canadian decision-makers. CCCma made key contributions to *Canada's Changing Climate Report (2019)*, the first report in the current national assessment process and is expected to make similar contributions to future reports as part of the ongoing, national assessment process. *Canada's Changing Climate Report* provides the foundational physical climate science to underpin mitigation and adaptation planning in Canada.

CCCma is also a world leader in seasonal to decadal prediction, being one of four Global Producing Centres (GPCs) for the World Meteorological Organization (WMO) Lead Centre for Annual to Decadal Prediction (LC-ADCP). CCCma develops models and methodologies underlying ECCC's operational Canadian Seasonal to Interannual Prediction System (CanSIPS) and its suite of seasonal forecast products, and coordinates CanSIPS contributions to international operational and research activities.

Most recently, the Government of Canada responded to the growing demand of Canadians for climate information and data by creating the Canadian Centre for Climate Services (CCCS). CCCma provides CanESM projections that, as part of a multi-model ensemble, underpin future climate change scenarios for Canada that are disseminated by the CCCS.

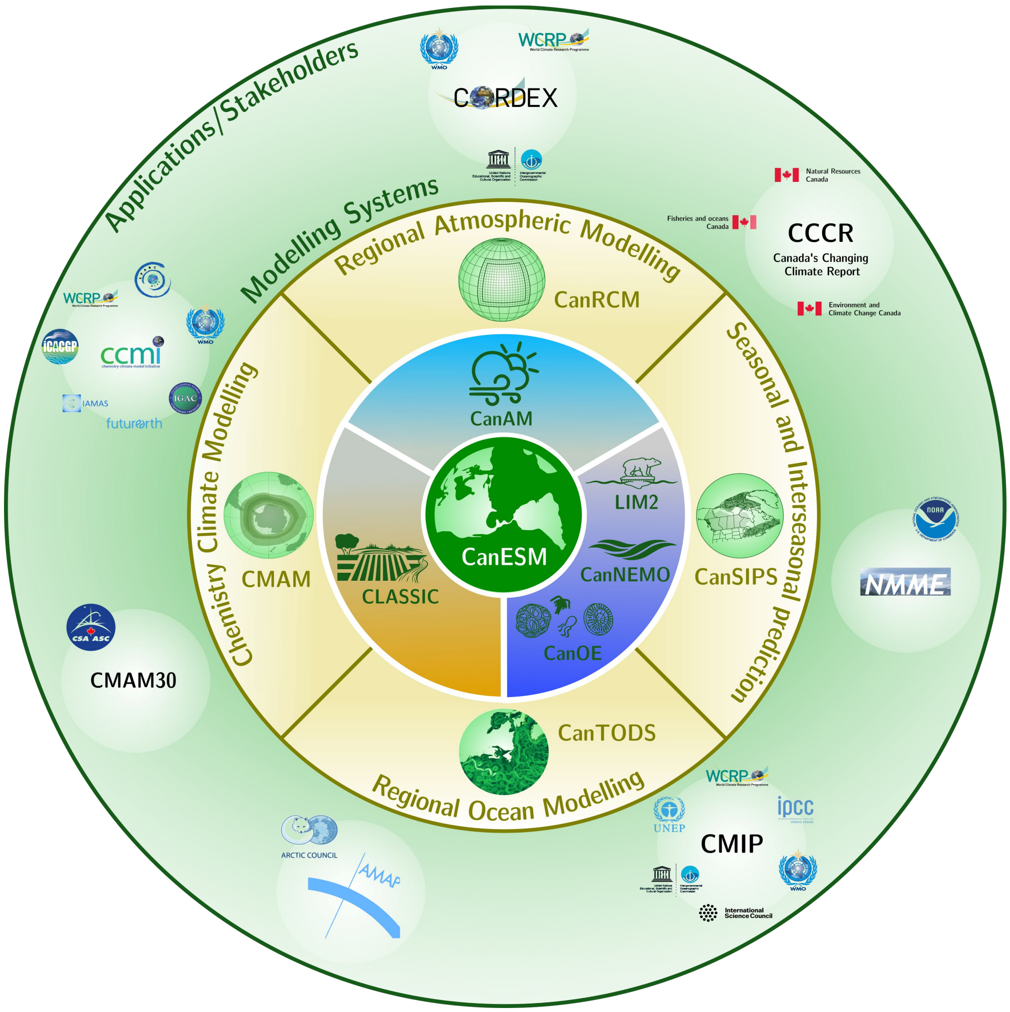


Figure 5. The CCCma integrated modelling system and its connections to major international coordinating bodies and projects including the Coupled Model Intercomparison Project (CMIP), Coordinated Downscaling Experiment (CORDEX), North American Multimodel Ensemble (NME), and Chemistry Climate Initiative (CCMI) and assessments, including Canada's Changing Climate Report, IPCC Assessment and Special Reports, WMO Ozone Assessments, and AMAP Report

Our ambition for the next decade

The primary goal of this plan[1] is to ensure that CCCma will maintain the ability to effectively address the key emerging scientific questions related to climate change, and fulfill its commitments to provide relevant and timely science-based information to support decision-making, adaptation action, and mitigation policy development in Canada and internationally. This plan envisions continued collaborative development of CanESM as the foundation of a comprehensive integrated modelling system, with component parts that are adapted for application in downstream modelling systems and are responsive to the needs of additional clients (Figure 5). Developing applications within the framework of a single, integrated modelling system will promote efficiency and internal collaboration, as

[1] This plan was informed by a comprehensive strategic review process. See Annex 1 for information about this process.

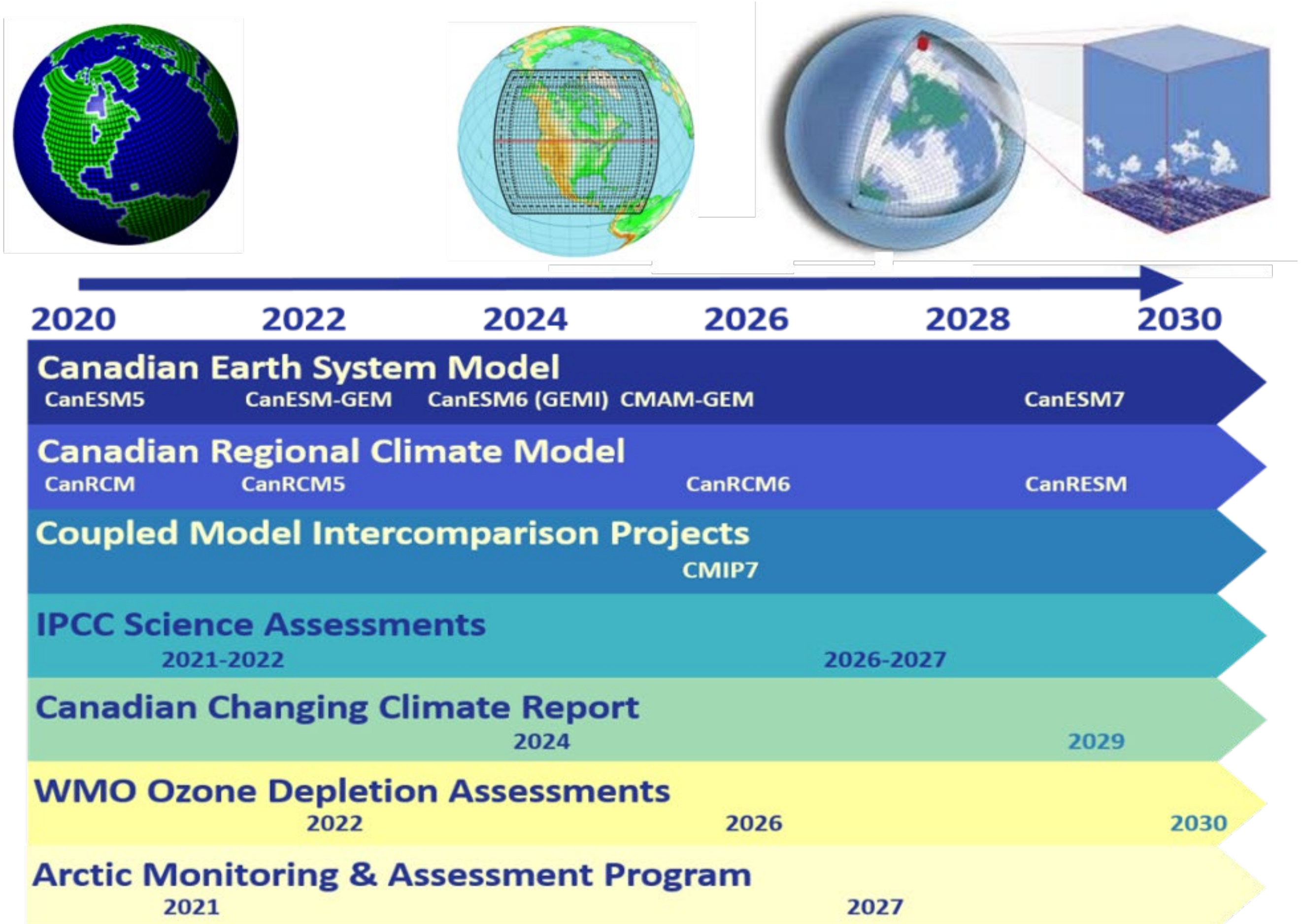


Figure 6. Timeline of CCCma modelling evolution and major science assessments over the next 10 years.

well as providing seamless products across applications.

As scientific knowledge of the climate system advances, continuous improvements to existing Earth System Model components are required to maintain state-of-the-art, scientifically robust and efficient modelling capacity. The key international and national commitments and the anticipated timing and deadlines imposed by these activities and projects are a key consideration in the planning of our activities over the next 5-10 years (Figure 6). There is also a growing demand for quantitative future climate predictions and projections that are more resolved, represent more complex chemistry, and are Canadian focused. More accurate projections of sea level rise in oceans surrounding Canada, projections of changes in ocean temperature and salinity, and of ocean currents are also in high demand to support coastal and marine risk assessments. To address these emerging scientific priorities, an increase in scientific and technical capacity is required. As the High Performance Computing landscape evolves, significant investment in climate model software optimization is also required to increase efficiency, which will both optimize the performance and limit the carbon footprint of Earth system modelling. Increased collaboration between CCCma and partner organizations is vital to maintaining the globally recognized, state-of-the-science Earth system modelling capacity required to meet the growing scientific and technical demands described above.

Challenges and opportunities in the next decade

Investments to date in CCCma's ESM program have borne impressive results. CCCma's Earth System Model and its derivatives have been internationally recognized for their quality. As a result, the outputs from these systems are widely used. CCCma has amassed significant scientific and technical expertise from decades of ESM development and participation in internationally coordinated climate modelling activities. As such, the CCCma program is a solid and logical base from which to continue developing Earth system modelling applications in Canada. With new strategic investments and a focused mandate, CCCma can deliver the collaborative, integrated, Canadian Earth system modelling framework needed to produce high-resolution, Canadian-focused predictions and projections of the full suite of climate-relevant Earth system components. By design, this system will enable CCCma to continue meeting demands for global model products. By striving towards an open-standards-based collaborative modelling framework, CCCma can leverage the expertise of the broader Canadian climate science community, thus, helping to maintain a world-leading standard of scientific quality and technical efficiency. This system will provide the best possible scientific basis for informing decisions in Canada.

However, new investments in the program are required to realize these advances because the resourcing decisions made in 2007 have not kept pace with the growth in demand for adaptation- and mitigation-relevant climate projections. CCCma is at a critical juncture where a renewed commitment to maintaining the calibre and domestic relevance of the modelling system is needed, backed up by the resources to fulfil this commitment. CCCma faces several key challenges. The first major challenge is maintaining a state-of-the-science representation of the climate system. This requires the continuous development and improvement of existing model components, and specifically the physical and biogeochemical parameterizations employed to represent Earth system processes. While development of parameterizations has proceeded, a lack of capacity, and diversion of existing scientific effort away from model development means that several key processes are falling behind the international scientific standard (e.g., the representation of climate critical features such as clouds in the atmosphere, and ice sheets). Additional research capacity, and a refocusing of existing resources on core model development and analysis is required to remain relevant.

The second major challenge is the technical state of the climate model code and supporting software that facilitate application of the model on ever evolving high performance computing platforms. There has been little focus on technical development of the model for the past several decades. While the integrated model has functioned on successive generations of HPC systems, modernizing the climate model code to take full advantage of new high performance computing systems is essential to running efficient simulations. Efficiency is critical given the increasing demands for high resolution simulations that are computationally expensive. The lack of technical capacity in CCCma has led to the accumulation of a significant *technical debt* that is becoming crippling. CCCma's capacity to continue to deliver on ongoing commitments while also responding to the increasing demands for more simulations, higher resolution simulations, more detailed output and additional complexity is in jeopardy without focused investments in technical modernization.

Addressing this technical debt provides an opportunity to modernize the foundation of the CanESM codebase, which underlies all scientific applications of the model. This technical development will focus on creating a modelling foundation that is robust, efficient, and designed to support interoperability and collaborative development. Embracing open community standards and leveraging community tools will allow both the technology and skills of code developers to be more transferable, and will support the Open Government science objective. Increased efficiency and standardized operation will allow CCCma to meet the growing demands noted above. CCCma will also continue to develop each individual model component to remain up-to-date with the emerging science. Increased focus and investment in both *technical* and *scientific* development are key to ensuring that the CCCma modelling system remains state-of-the-science, and capable of addressing key scientific and policy-relevant questions. These advances can only be realized through investments in human resources. In this regard, a number of critical scientific and technical positions have been identified to enable the maintenance and advancement of CCCma's Earth system modelling capabilities.

The critical need for maintaining a state-of-the-science Earth System Model underpins many of the commitments in the document *Climate Science 2050: Advancing Science and Knowledge on Climate Change (CS2050)*. This document describes the scientific requirements for building a carbon neutral and climate resilient society in Canada. CS2050, developed in consultation with science and knowledge generators and users, emphasizes the essential role of ESM in informing actions to ensure:

- healthy and resilient Canadians, communities, and built environments;
- a carbon-neutral society;
- resilient terrestrial and aquatic ecosystems; and
- sustainable natural resources.

To this end, a number of core priorities in Earth system science are identified in CS2050. For example, advancing understanding of how weather and climate extremes are projected to change in a changing climate is a priority given the potential damages associated with such events. While robust information on changes in some types of extremes, in particular temperature extremes, can be provided by the current generation of Earth system models, improved projections of changes in storms and associated precipitation extremes requires advances in Earth system modelling. Improved understanding of both the impacts of climate change in the Arctic and the vulnerability of stores of carbon in Arctic ecosystems to climate warming will be possible with enhanced representation of Arctic features such as permafrost in CanESM's framework. Also, advanced Earth system models with comprehensive biogeochemistry are required to provide insight into the efficacy of mitigation options. This includes improved understanding of carbon sequestration potential in both land and marine ecosystems, and of the climate response to mitigation of short-lived climate forcers. The efficacy and unintended consequences of potential climate engineering approaches can also be explored with such models.

Scientific Priorities

Climate information requirements are focused increasingly on quantities that go beyond traditional 'physical climate' variables. Therefore, while reducing uncertainties in projections of temperature, precipitation, snow, sea ice, etc., including their extremes is still needed, there is now a growing demand for information on changes in the carbon cycle, aerosols and air quality, and terrestrial and marine ecosystems. Integrated assessment of environmental issues also applies to ocean science, with increasing demands for improved projections of changing ocean currents and ocean conditions for both climate change and pollution monitoring and management.

These demands for more comprehensive analysis of the consequences of climate change, and responses to it, are driving model development. Model development is necessary to represent the physical processes, interactions, and feedbacks that connect the carbon cycle, sulphur cycle, nitrogen cycle and ecosystem components to the physical system and its change. It is also essential that we maintain the capability to undertake carefully constructed model experiments and analyses of their results in order to ensure that we are credible and able to respond to present and future needs for robust climate science information and advice. Sustaining this leading science capability within the Canadian government will ensure Canadians can leverage the scientific advances of others and that Canadian policymakers have direct access to this in-house expertise.

This Plan identifies seven (7) scientific priorities for Earth system modelling that respond to the growing demand for more comprehensive analysis of climate change, its consequences and response options. These priorities respond to both the need to fundamentally reinvest in our core strength of developing and maintaining a state-of-the-science Earth System Model, while also applying our model to advance actionable science aligned with the priorities of CS2050. The first priority (1) addresses the two key scientific challenges of the program, namely, the maintenance of a state-of-the-science representation of the climate system; and, modernizing the existing model code to take full advantage of new high performance computing systems. The first priority also recognizes that a high-quality global model is the necessary starting point for subsequent downscaling, which uses a regional climate model to provide more spatial detail over Canada as needed by users from a range of disciplines. Priorities two (2) to seven (7) address the priority needs of Canadian society for climate change projections as described in CS2050, namely, science to support the achievement of carbon neutrality in Canada, and to build healthy and resilient communities and ecosystems.

Priority Area 1 – The Changing Earth System – Past and Future

Goal Statement: CCCma will advance our fundamental understanding of the Earth system and will improve simulations of the response of this system to changes in human and natural drivers.

Key outcomes of the research under this priority include the following:

- Improved representations of existing model processes (e.g., clouds) and the addition of important new processes (e.g., permafrost) in order to reduce uncertainties related to climate system feedbacks;
- Increased model resolution to improve the representation of physical and biogeochemical processes, to reduce model uncertainty, and to provide more detailed regional climate information;
- Improved quantification of policy relevant environmental metrics, such as global carbon emissions budgets consistent with limiting global warming to the commitments of the Paris Agreement;
- Determination of causes of historical climate change (detection and attribution), including at regional scales and for climate extremes;
- Reduction in uncertainties in projections of climate change; and,
- Utilization of global models as the basis for statistically downscaled projections of changes in regional and local climate.

Priority Area 2 – Detailed Regional Climate Information for Canadian Decision-Makers

Goal Statement: CCCma will respond to the increasing demands for higher resolution projections of climate change in order to support adaptation decision-making. The Canadian Regional Climate Model (CanRCM) will be further developed to meet the increasing demand for higher resolution projections of climate change. Furthermore, the new Canadian Three Oceans Downscaling System (CanTODS) will provide consistent, high resolution, ocean and sea-ice projections for Canada's three oceans. The outcome of coupling of CanRCM to CanTODS will be a Regional Earth System Model, CanRESM.

Global climate models are too computationally expensive to provide fine resolution regional climate change information. There are two complementary approaches to developing higher resolution projections of climate change, both of which depend on global scale models. Dynamical downscaling uses a climate model run at higher resolution over a particular sub-region to provide additional detail, while being constrained to follow the global climate evolution given by a specified global parent model at the boundaries of the region. Thus, dynamical downscaling is effectively a zoomed-in version of a global climate model, and represents all of the dynamical climate processes as they evolve, but also its model biases. Statistical downscaling uses statistical relationships based on the historical climate to refine climate model results to a more local scale, and to correct model biases. These statistical relationships can be applied to future projections from global or regional dynamical models to provide more resolved information, but they make the fundamental assumption that the statistical relationship will not change in the future. In general, the approaches are complementary and nested: global models represent Earth system climate evolution, dynamical downscaling refines this information for a regional spatial domain, and statistical downscaling bias corrects and further refines the best available projections to the local scale.

The Regional Climate Models (RCMs) used for dynamical downscaling thus represent a key link in the process used to produce climate information that is relevant to, and supportive of, effective national policy and regulatory decision-making. Regional climate models include enhanced representation of regional topographical features, which in the case of Canada includes representation of the Great Lakes and Rocky Mountains among other features. CanRCM has been used for international assessments such as the Coordinated Regional Downscaling Experiment and for over 50 climate change impacts studies by Canadian researchers.

A coupled regional Earth system model more realistically represents the key climate change processes that will influence Canada, and hence adds value to atmospheric- or ocean-only downscaling. Consequently, CCCma will aim to produce a regional Earth system model, CanRESM, based on the coupling of CanRCM to the new regional ocean model, CanTODS.

Key outcomes of the research under this priority include the following:

- Development of CanTODS;
- Provision of consistent, high resolution ocean and sea-ice projections for Canada's three oceans; and
- Provision of seasonal predictions for both atmospheric and ocean variables using CanRESM as an operational model within the Canadian Seasonal and Interannual Prediction System; and,
- The additional coupling of CanRCM to CanNEMO in CanRESM to represent resolved lakes providing a more physically

based representation of watershed run-off to improve the interface with hydrological models; a better representation of future changes in extreme events in the Great Lakes region; and better predictions of future drought patterns and the occurrence of flooding.

Priority Area 3 – The Carbon Cycle Earth System Feedbacks

Goal statement: To improve the representation of terrestrial and marine ecosystem and carbon cycle components in the CanESM framework in order to better understand the role of biogeochemical feedbacks in the Earth system, and to better quantify the sensitivity of the climate system, including Arctic ecosystems, to anthropogenic carbon emissions.

Anthropogenic climate change is fundamentally about human perturbation of the natural carbon cycle. Atmospheric carbon dioxide (CO_2) concentrations remain stable when emissions of carbon to the atmosphere are balanced by carbon uptake from the atmosphere. Due to emissions of CO_2 from human activity, atmospheric CO_2 concentrations have risen steadily since the pre-industrial period, even though natural land and ocean carbon sinks have removed about half of the human-emitted atmospheric CO_2. The interactions between the physical climate system and the carbon cycle ultimately govern the response of the climate system to increasing anthropogenic CO_2 emissions. The CanESM framework includes representation of land, ocean and atmospheric carbon cycles and is well suited to address global-scale questions related to future changes in (including potential weakening of) carbon sinks in response to global warming and other climate changes. Improved representation of carbon cycle components and feedbacks in CanESM will lead to improved estimates of how much carbon can be emitted by human activities while limiting the rise in global temperature to different levels.

More specifically, the strategic plan for CanESM's land component (Canadian Land Surface Scheme Including biogeochemical Cycles, CLASSIC) will focus on continued model development but also its application. CLASSIC is developed jointly by two sections within the Climate Research Division, CCCma and the Climate Processes Section. Scientific developments will include representation of high-latitude processes such as those involving permafrost carbon and Arctic shrubs. Currently, there is a lot of uncertainty about how much carbon will be emitted from thawing permafrost in a warming climate, and the extent to which these emissions might be offset by a 'greening Arctic'. Representation of the nitrogen cycle along with other processes is important for realistically simulating Arctic ecosystem changes and global land carbon uptake in response to increasing atmospheric CO_2. Among other applications, the application of CanESM's land model at 0.22° resolution over Canada is a major exercise that is currently underway to quantify natural carbon sinks and sources over Canada and their changes over time. CCCma will continue to contribute to international, land-focused, model-intercomparison projects such as the Trends in Net Land–Atmosphere Carbon Exchange (TRENDY). This activity contributes directly to the annual assessments of the global carbon cycle by the Global Carbon Project.

The ocean biogeochemistry components of CanESM are developed collaboratively with Fisheries and Oceans Canada. The Canadian Model of Ocean Carbon (CMOC) is a reduced complexity model that can be run affordably at higher resolutions and in large ensembles, while the more comprehensive Canadian Ocean Ecosystem Model (CanOE) is more suited to specific scientific questions. The key strategic objectives for this component of CanESM is to improve representations of key processes in the carbon and nitrogen cycles in both these models; representing additional climate active gases such as nitrous oxide (N_2O) and dimethyl sulphide (DMS) in CanOE; and migrating CMOC to higher ocean resolutions (0.25°) within CanESM. The new Canadian Three Ocean Downscaling System (CanTODS) (see priority 2 above) will provide high resolution, regionally relevant information on ocean climate impacts in Canadian waters, and will help to quantify ocean carbon sources and sinks in Canada's three oceans.

Key outcomes of the research under this priority include the following:

- Improved projections of global land and ocean carbon sources and sinks under different scenarios of climate change and better quantification of the response of these systems to continued climate warming;
- Improved estimation of the remaining global carbon emissions budget to meet given global temperature targets; and,
- Improved characterization of the response of Canada's terrestrial and ocean ecosystems to projected changes in atmospheric CO_2 and climate warming.

Priority Area 4 – Seasonal to Decadal Climate Prediction

Goal statement: CCCma will improve its seasonal to decadal (S2D) prediction system and expand the number of climate metrics forecasted by this system to deliver products tailored to specific sectors, and eventually individual users.

A key application of CCCma's models is to predict the evolution of the climate system over the next season to decade, a timeframe that is relevant to many kinds of activities/decisions. Besides providing a basis for ECCC's seasonal forecasts, CCCma's models contribute to WMO seasonal and decadal forecasting operations, and to international research aimed at better understanding climate predictability and improving climate predictions in service to society, which together constitute a strategic priority of the World Climate Research Program (WCRP). On these timescales, natural variability in the climate system can have a marked influence on the near-term evolution of the climate that competes with or exceeds anthropogenic changes. Climate *prediction* (versus *projection*) requires initializing model components based on the observed state of the climate system at the start of the forecast, in contrast to long-term climate simulations for which initial conditions are largely irrelevant. As a result, S2D predictions are more confident about the near-term evolution of the climate system.

Climate prediction research at CCCma (often in collaboration with the Meteorological Research Division) has underpinned the development of ECCC's operational seasonal forecasts since the 1990s, first out to 3 months using atmospheric circulation models and more recently out to 12 months using coupled climate models. ECCC's seasonal forecasts are recognized as among the most skillful, including for predicting future El Niño and La Niña events that strongly impact Canada. As a result, CCCma contributes to a number of international operational and research activities. CCCma has been at the forefront internationally of several aspects of climate prediction research. These include extending the range of Earth system variables that can be usefully predicted (e.g., snow, sea ice), processing of model outputs to provide optimally useful forecast information, and developing capabilities for decadal prediction in association with WMO and CMIP.

That said, there are a number of key sources of uncertainty in S2D systems. These uncertainties include the identification and parameterization of sources of climate predictability, the most effective approach for initializing climate models, and the best approach for extracting probabilistic information about future conditions from climate prediction ensembles in order to serve society. As such, CCCma will focus its efforts on addressing these issues.

Key outcomes of the research under this priority include the following:

- Refinement of CCCma's core modelling capabilities to ~1° atmospheric and 1/4° ocean resolution to better represent Canada's regions and to stay current with global modelling standards for S2D prediction;
- New S2D prediction applications in the areas of air quality prediction, operational extreme event attribution (see priority 5 below) and downscaled coastal ocean prediction to support marine resource management (see priority 2 above); and,
- Development of tailored, sector-specific S2D information for Canada in association with CCCS and ECCC's Canadian Meteorological Centre and Canadian Ice Service.

Priority Area 5 – Climate Extremes and Extreme Event Attribution

Goal statement: CCCma will provide timely and credible information on the role of anthropogenic climate change in high impact climate events and on future changes in climate extremes in Canada to support climate risk management.

Extreme weather and climate events are key drivers of climate impacts in Canada, including extreme rainfall events, hot and cold extremes, and extreme fire weather. This priority area encompasses research on extreme events, including understanding of their drivers, and projected changes, and the relatively new area of extreme event attribution. Extreme event attribution aims to answer questions about changes in the likelihood of an extreme event in response to anthropogenic climate change. Results from these analyses are used by the financial and insurance sectors to assess risk and are useful for public engagement on the consequences of climate change.

CCCma is well established in the area of extreme event research, including in the development of comprehensive multi-model projections of future changes in extremes, and more recently in event attribution, leveraging large-ensembles of CanESM simulations to publish studies including on cryospheric extremes and extreme fire seasons in Western Canada. Despite recent developments, there remain substantial uncertainties in event attribution results due to the sensitivity of these results to how the event is defined, the models used for the attribution, and the design of the analysis approach.

Research is planned to support the development of a near real-time quasi-operational system for event attribution using a high resolution version of the Canadian atmosphere model (CanAM). This will involve running two large ensembles of atmosphere-only simulations (with and without anthropogenic influence) to quantify anthropogenic influence on the probability of extreme events, and updating these regularly. This research area would include consideration of better techniques for removing anthropogenic influence from ocean surface temperatures and sea ice distributions, and possible application of the Canadian Regional Climate Model (CanRCM) to downscale simulations to higher resolution. Such a system would have the capacity to inform event attribution assessments of extremes such as heatwaves or droughts, shortly after they occur, and parallels operational event attribution systems in development at other international modelling centres.

Key outcomes of the research under this priority include the following:

- Development of a system suitable for transfer to operations for extreme event attribution using an updated version of CanAM based on the Global Environmental Multiscale Model (GEM) dynamical core at ~37 km resolution; and,
- Assessment of the anthropogenic influence on the magnitude and probability of major Canadian extreme events through the application of this system in hind cast mode and in near real-time.

Priority Area 6 – Role of Short-lived Climate Forcers

Goal Statement: CCCma will improve its representation of aerosols and chemistry in CanESM and use this capacity to provide improved estimates of the climate and air quality co-benefits of mitigation of short-lived climate forcers.

Short-lived climate forcers (SLCFs)—black carbon, methane, ground-level ozone, and sulfate— contribute significantly to climate change. These gases and aerosols remain in the atmosphere for much shorter periods of time than CO_2, yet their potential to warm (or cool) the atmosphere can be many times greater. Certain SLCFs are also dangerous air pollutants that have harmful effects for people, ecosystems, and agricultural productivity. Previous research shows that in addition to achieving net zero global CO_2 emissions, substantial reductions in SLCFs with climate warming effects is needed to meet the temperature goal of the Paris Agreement. However, very substantial scientific challenges still exist regarding the scope and magnitude of SCLF impacts on climate. According to Intergovernmental Panel on Climate Change (IPCC) estimates, uncertainties in the radiative forcing of climate are largely attributable to SCLFs, which are associated with atmospheric processes that involve interactions between aerosols, ozone, clouds, and radiation.

CCCma has successfully applied existing models to provide evidence for a wide range of impacts of SLCFs on climate in the 20th century, including the Arctic climate, and to evaluate how mitigation of SLCFs can provide near-term climate benefits. Additionally, CCCma contributed to assessments of ozone and climate by the WMO, which showed the benefits of controlling short-lived substances (such as hydrochlorofluorocarbons) that both contribute to ozone depletion and climate warming. However, aerosol and chemistry modules of CanESM are under continuous development to advance the range of applications of our model and to reduce uncertainties in the radiative forcing from short-lived climate forcers. Future SLCF model development and research at CCCma will continue to address scientific and policy development needs for climate and air quality.

These advances will be accomplished primarily by broadening the scope of current model development activities to include a more highly interactive treatment of individual SLCFs, the carbon cycle, and other components of the climate system in CanESM. These changes will benefit from improvements made in the biogeochemical processes on land and in the ocean in CanESM. In addition, improvements to the representation of SLCF emissions from vegetation fires in CanESM and potential future climate engineering applications will advance our understanding of SLCFs and climate change. Given the wide scope of these activities, research collaborations with other research divisions, other government departments, and academia will be critical to the success of these activities.

Key outcomes of the research under this priority include the following:

- Improvements in the representation of tropospheric chemistry (e.g., volatile organic compounds (VOC) chemistry) in the context of climate simulations;
- Incorporation of outputs from the CLASSIC model such as permafrost emissions of methane, wildfire emissions and plume rise into CanESM; and,
- Application of this system to inform Canada's Changing Climate Report, WMO O_3 Assessment reports, Arctic Monitoring and Assessment Program (AMAP) SCLF Assessment reports, and projects under the World Climate Research Programme's Chemistry Climate Modelling Initiatives.

Priority Area 7 – Implications of Climate Engineering and Response to Mitigation Options

Goal Statement: Use CanESM to simulate and analyse climate impacts of solar radiation management, carbon dioxide removal and other mitigation options, either individually or simultaneously.

We are moving from an era where the key role of climate modelling was to investigate the human influence on observed climate change and to provide large-scale, long-term projections of future climate change to the post-Paris Agreement era where the focus is on informing climate change adaptation and mitigation actions. While these mitigation actions can include climate engineering in the form of carbon dioxide removal (CDR), there remains another form of climate engineering, solar radiation management (SRM), which intervenes by adjusting the amount of radiation entering the Earth system. Like CDR, SRM can take multiple forms including injection of reflective particles into the upper atmosphere, modifying clouds to make them reflect more sunlight, and brightening the Earth's surface. The focus of this priority area is improved simulation and analysis of the effectiveness and potential unintended consequences of climate engineering, providing needed information to inform the consequences of real world implementation. CCCma is already well established in modelling and analysis of climate engineering and more generally to inform climate change mitigation policies.

CCCma has ongoing involvement in international efforts to understand the effects of climate engineering by contributing SRM simulations to the Geoengineering Model Intercomparison Project (GeoMIP) and by contributing CDR simulations to the Carbon Dioxide Removal Model Intercomparison Project (CDRMIP). As interest in climate engineering grows and the potential for its deployment increases, it is necessary to be able to assess its impacts. To support analysis of climate engineering impacts, we will make use of well-established approaches at CCCma including production of large ensembles.

Simulation of the response to climate engineering requires that CanESM represent relevant processes. Specific processes that are important for simulating SRM include interactive stratospheric aerosols, and processes related to known impacts, for example, interactive ozone and the carbon cycle. Continued involvement with the Geoengineering Modelling Research Consortium will (GMRC) will help guide and focus research for SRM-specific model processes.

To date, CCCma has used bespoke simulations including scenarios of black carbon mitigation to examine the climate and Arctic climate effects of black carbon mitigation in Arctic Council countries (see priority area 6 above) and contributions to studies on detection of the climate effects of the Montreal Protocol. Detection and attribution will be used to inform the impacts of emissions mitigation options relative to business-as-usual emissions. Policy-responsive simulations and analysis using input from within ECCC and other government departments will be developed on an as-needed basis to address Canadian-focused policy questions, beyond those that can be answered by large international intercomparison studies. The exception may be simulations of some specific mitigation options such as the climate impacts of aviation mitigation that would require additional capacity and associated resources beyond those required to do other types of SRM and CDR simulations.

Key outcomes of the research under this priority include the following:

- The capacity to model the injection of aerosols into the stratosphere, a proposed Solar Radiation Management (SRM) methodology, and associated processes including interactions with chemistry; and,
- Development of a research program using CanESM to simulate proposed SRM and carbon dioxide removal (CDR) scenarios and subsequently analyse the potential global, regional and Canadian climate impacts of these scenarios.

Resources needed to realize this plan

In parallel with developing this strategic plan, a set of concrete roadmaps were developed at CCCma to advance this work on three time horizons, short (1-3 years), medium (5-7 years) and long-term (10+ years). These roadmaps lay out detailed scientific and technical tasks and their associated milestones to modernize the foundation of the Earth system model, which underlies all scientific applications of the model, and to address emerging scientific questions within each of the priority areas listed above.

CCCma is well positioned to provide the best possible scientific basis for informing decision-making in Canada through achieving these milestones, which are fully aligned with the seven priorities described here. Realizing these milestones however is only possible with new and focused investments in key *technical* and *scientific* capacity.

In order to implement this plan in the short-term, it is vital to invest in a number of critical scientific and technical positions identified via an associated human resource planning exercise. Bringing these critical technical and scientific staff on board will enable CCCma to create a robust and efficient modelling foundation. Another key requirement for the successful implementation of this plan is continuous and significant investment in climate model software optimization to increase efficiency and standardized operation of CanESM. Furthermore, collaborations between CCCma and partner organizations will need to continue and to expand, not only to realize this plan but also to support the Open Government science objective of an open standards-based collaborative modelling framework. The outcome of these investments will be timely, relevant knowledge and information in the service of Canadian society striving for resilience to climate change over the next decade.

Implementation of Strategic Plan

An implementation plan for this strategic plan was developed as part of the strategic planning process. It is published as a companion document to the strategic plan and is comprised of roadmaps for advancing the scientific priorities for three time horizons, short (1-3 years), medium (5-7 years) and long-term (10+ years).

Conclusion

As the impacts of climate change increasingly alter the state of our physical environment, the need for a rigorous scientific understanding of future environmental conditions becomes more pressing. Canada's Earth System Model (CanESM) is one a handful of unique systems capable of simulating climate change and is the product of decades of federal investments to develop a sovereign capacity to project our future and understand our options for mitigation and adaptation. This plan highlights CCCma's scientific priorities for Canada's Earth system modelling research program. Research and development focused on these priorities is required to deliver timely, relevant knowledge and information to Canadians and others striving to mitigate and adapt to climate change over the next decade. These priorities, and the accompanying implementation plan, build on CRD's strong scientific leadership and foundational capacity in this scientific domain and leverage the scientific computing and monitoring technology advances of the past decade to enable ECCC to maximize its contribution to informing responses to Canada's current adaptation and mitigation challenges.

Annex 1: Process for Developing the Strategic Plan

Following the Climate Research Division's strategic planning workshop in February 2019, CCCma held its third strategic planning workshop on December 3rd and 4th, 2019 in Victoria, British Columbia. The primary goal of this workshop was to create a strategic plan that consolidated the vision and mission of the section and that would serve as a guide for work planning and program investments.

Prior to the workshop, there was a pre-workshop survey to inform the workshop's discussion on CCCma challenges, including an expanding set of activities, limited resources, an ageing technical infrastructure and model code base, expanding demands from clients, and paradigm shifts in supercomputing. The workshop was structured to enable interactive discussion of challenges, solutions, and future directions for the section. The format included full group discussions, break-out groups, and presentations. The outcome of the workshop was a unified vision for the future of CCCma, which was informed by broad input from across the section. After the workshop, staff participated in a survey to collect a list of lessons learned from the workshop process.

From January to March 2020, the CCCma team organized themselves into seven working groups, aligned with the priority themes identified at the workshop, and collaboratively developed roadmaps for advancing these scientific priorities for three time horizons, short (1-3 years), medium (5-7 years) and long-term (10+ years). Once these working groups completed their work, the section held two, full-staff consultation sessions on the contents of the roadmaps. The outcome was six sets of roadmaps for each scientific priority, a merged overall CCCma roadmap, and the first draft of CCCma strategic plan.

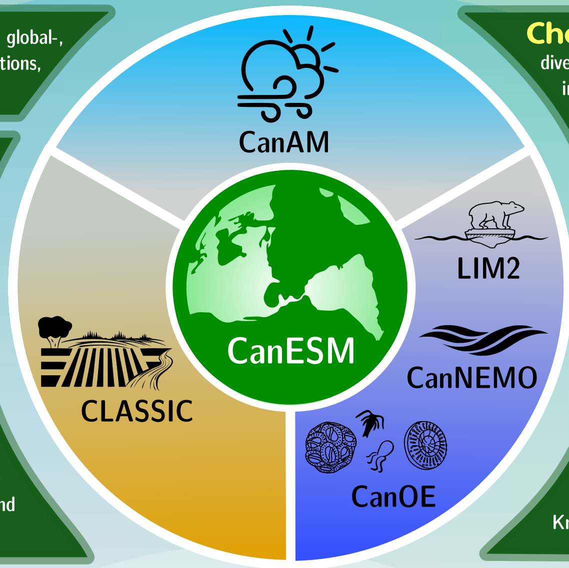
From April to June 2020, the first draft of CCCma strategic plan underwent two CCCma internal reviews and, with support of the CRD Senior Science Advisor, a second draft was developed that was further developed and reviewed by the CRD Director. The outcome of this extensive process is the current CCCma strategic plan that lays the path for advancing the work of the section over the next decade.

CCCma Strategic Plan (2020-2030) | Overview

Vision To serve as the national focal point for global-, continental-, and regional-scale climate change projections, analyses, and scientific information for Canadians

Mission To provide robust climate predictions and projections over Canada and the globe through the continuous development and innovative application of Canada's suite of Earth System models and scientific analysis of their output

Capacity CRD leads the development and application of a tightly integrated suite of Earth System models. At the heart of this system is the global, fully-coupled Canadian Earth System Model, CanESM, which is comprised of models for the atmosphere, CanAM; ocean, CanNEMO; land surface and terrestrial ecosystem, CLASSIC; sea ice, LIM2; and ocean biogeochemistry ecosystem, CanOE



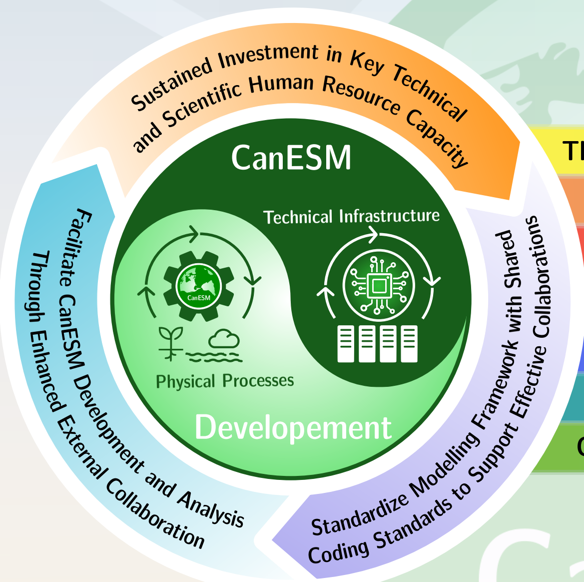
Challenges There is an urgent need to answer more diverse science-policy questions with greater specificity requiring physical processes to be modelled more realistically and in ever increasing detail. This has necessitated improved model efficiency and enhanced scientific capacity

Goals To be the foundation of a comprehensive, integrated, modelling infrastructure within the Canadian community, interfacing with downstream modelling systems and providing relevant climate change information to Canadian decision makers

Opportunity The need to sustain Canada's state-of-the-science Earth system model underpins many of the information requirements identified by Canadian decision makers and stakeholders in the GOC report, Climate Science 2050: Advancing Science and Knowledge on Climate Change

History/Impact Over the past four decades, CCCma has developed a state-of-the-science, global-scale, climate modelling capability and is the sole Canadian provider of comprehensive Earth system modelling capacity. Our scientific leadership in the field of Earth system modelling means that CRD's research scientists are an integral part of the international research community's efforts to understand and project climate change by spearheading ongoing developments, influencing international science research strategies, and acting as ambassadors for Canadian climate science. Such deep international connections allow our scientists to integrate scientific and technological advances of the international community into Canada's model development, applications and analysis efforts, thereby improving the quality and robustness of climate information products. The development of such expertise within the Canadian government means that Canadian decision-makers have the highest level of expert scientific advice available to them to support policy and regulatory deliberations related to climate change

Investment



Priority Areas

Action Plan

Priority Area	Action
The Earth System - Past and Future	Modernize the existing CanESM codebase; further develop existing model components; introduce representations of new processes to advance our understanding of the Earth system and improve the response of the system to human drivers
Regional Climate Information	Further develop the Canadian Regional Climate Model to meet the increasing demand for higher-resolution projections of climate change; add new regional ocean modelling capacity to CanESM to provide high-resolution, sea-ice projections for Canada's three oceans
Carbon Cycle Feedbacks	Improve the representation of terrestrial and marine ecosystem, and carbon cycle components in CanESM to advance our understanding of the role of biogeochemical feedbacks and to better quantify the sensitivity of the climate system to anthropogenic carbon emissions
Seasonal to Decadal Prediction	Improve Canada's seasonal to decadal prediction system and expand the number of climate metrics forecasted to allow the development of products tailored to specific sectors and eventually individual users
Extreme Event Attribution	Provide timely and credible information on the role of anthropogenic climate change in high-impact climate events and on future changes in climate extremes in Canada to support climate risk management; ultimately develop an operational system for extreme event attribution
Role of Short-lived Climate Forcers	Provide improved estimates of the climate and air quality co-benefits of mitigation of short-lived climate forcers by improving representation of aerosols and chemistry in CanESM
Climate Engineering and Mitigation	Use CanESM to perform geoengineering experiments employing solar radiation management, carbon dioxide removal scenarios and other mitigation strategies to evaluate the potential global, continental and Canadian climate impacts

CanESM

Annex 2: Essential Terminology

- **Adaptation**
  Process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.
- **Aerosols**
  Tiny airborne solid or liquid particles, with a typical size between 0.01 and 10 µm, that stay in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in several ways: directly through scattering and absorbing radiation, and indirectly by acting as cloud condensation nuclei or ice nuclei, modifying the optical properties and lifetime of clouds.
- **Anthropogenic**
  Resulting from or produced by human activities.
- **Attribution**
  Identifying the causes of an observed change or event in terms of the relative contributions of multiple causal factors.
- **Biogeochemical processes**
  Processes in which chemical substances (such as carbon) move through the biotic (living) and abiotic (non-living, such as water and rock) components of the Earth system.
- **Black carbon**
  A carbonaceous aerosol that is emitted as a result of the incomplete combustion of carbon-based fuels. Black carbon is operationally defined based on measurement of light absorption and chemical reactivity and/or thermal stability. It is sometimes referred to as soot.
- **Carbon cycle**
  The carbon cycle is the flow of carbon (in various forms, such as carbon dioxide) through the atmosphere, ocean, terrestrial and marine biosphere, and lithosphere.
- **Carbon emissions budget**
  The cumulative amount of carbon that can be emitted while keeping the global surface temperature increase to a given level, taking into account contributions of other greenhouse gases and climate forcing agents.
- **Carbon Cycle Earth System Feedbacks**
  A climate feedback involving changes in the properties of the land and ocean carbon cycle in response to climate change that can affect the flux of CO_2 between the atmosphere and ocean and between the atmosphere and the land biosphere. Also referred to as climate-carbon cycle feedback.
- **Integrated modelling system / CCCma integrated modelling system**[2]
  In this document, integrated modelling system refers to a collection of model components and supporting software tools that can be configured for use in a wide range of different scientific applications. The core model components are the atmosphere (CanAM), land surface (CLASSIC), ocean (CanNEMO) and coupler. An ecosystem of supporting software allows the models to run on HPC systems, and processes inputs and outputs to a usable format. These core components make up CanESM, which is deployed for long range climate simulations. In a modified configuration, these same components are applied for initialized seasonal to decadal predictions, as a part of CanSIPS, or for advanced atmospheric chemistry and stratospheric processes (CMAM). Different individual subcomponents maybe configured for higher resolution, regional simulations

[2] This term should not be confused with "integrated assessment models" (IAMs) which integrate knowledge from two or more domains into a single framework. For example, one class of IAM combines economic, demographic, and policy modelling with simplified physical climate models to make projections of population growth, economic development, land use, and the implications of different policy options for climate-relevant emissions and climate impacts.

of the atmosphere (CanRCM), land (CLASSIC) or ocean (e.g. CanTODS). All these configurations share common underlying components, infrastructure, and development philosophy, which is an efficiency that allows seamless integration across the modelling team and the resulting data products.

- **Climate**
  The average, or expected, weather and related atmospheric, land, and marine conditions for a particular location. In statistical terms, it is the mean and variability of relevant measures over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization.
- **Climate change**
  A persistent, long-term change in the state of the climate, measured by changes in the mean state and/or its variability. Climate change may be due to natural internal processes, natural external forcings such as volcanic eruptions and modulations of the solar cycle, or to persistent anthropogenic changes in the composition of the atmosphere or in land use.
- **Climate feedback**
  An interaction in which a perturbation in one climate condition causes a change in a second, and the change in the second ultimately leads to an additional change in the first. A positive feedback amplifies the original change, and a negative feedback dampens it.
- **Climate forcing agents**
  Factors that disrupt Earth's energy balance, forcing climate toward warmer or cooler conditions. Climate forcing agents can be either natural or anthropogenic, and the main agents are solar irradiance variations, volcanic eruptions, changes in atmospheric composition (including increases in greenhouse gases), and changes to the land surface. "Climate driver" has the same meaning.
- **Coupled Model Intercomparison Project**
  The World Climate Research Programme has established this project to coordinate, analyze, and archive a range of simulations and projections from multiple climate models.
- **Climate prediction**
  Climate predictions simulate evolution from initial conditions representing observed states of the climate system at a particular times. Climate predictions are classified based on their temporal extent as subseasonal (weeks), seasonal (months) or decadal (years), and represent combined impacts of predictable climate variability and assumed future changes in atmospheric composition.
- **Climate projection**
  A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases (GHGs) and aerosols, and is generally derived using climate models. Climate projections depend on the emission/concentration/radiative forcing scenario used, which is in turn based on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realized.
- **Detection**
  Demonstrating that an observed change in climate is inconsistent with internal climate variability. Changes in the climate become detectable if they are large when compared with internal climate variability.
- **Downscaling**
  Methods to transform global Earth system model results into more detailed, local to regional scale information that is better suited to adaptation planning and impact studies.
- **Earth system model**
  A coupled atmosphere–ocean general circulation model in which a representation of the carbon cycle is included, allowing for interactive calculation of atmospheric CO_2 or compatible emissions. Additional components (e.g. atmospheric chemistry), may be included. Coupled atmosphere–ocean general circulation models provide a comprehensive representation of the climate system,

among the most comprehensive of the suite of climate models currently available.

- **Ensemble**
  A collection of model simulations characterizing a climate prediction or projection. Differences in initial conditions and model formulation result in different evolutions of the modeled system and may give information on uncertainty associated with model error and error in initial conditions in the case of climate forecasts and on uncertainty associated with model error and with internally generated climate variability in the case of climate projections.
- **Greenhouse gas**
  Greenhouse gases are gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, by the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. There are also a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances.
- **Industrial period**
  The period in history, beginning around the mid-18th century and continuing today, marked by a rapid increase in industrial activity powered by the combustion of fossil fuels, and associated increases in emissions of carbon dioxide.
- **Internal climate variability**
  Variations in climate driven by processes internal to the climate system, including modes of climate variability — natural variations in climate with identifiable characteristics affecting particular regions over certain time periods. These modes include the well-known El Niño–Southern Oscillation as well as other such modes that recur in various parts of the world over varying time periods.
- **Likelihood**
  The chance of a specific outcome occurring, where this might be estimated probabilistically. In this report the likelihood of a result occurring is based on quantified measures of uncertainty expressed probabilistically (based on statistical analysis of observations or model results, or expert judgment). Likelihood is expressed quantitatively.
- **Mitigation**
  A human intervention to reduce the sources or enhance the sinks of greenhouse gases. A source is any process, activity or mechanism — natural or human — that releases greenhouse gases to the atmosphere. Conversely, a sink is any process, activity or mechanism — natural or human — that removes greenhouse gases from the atmosphere. In addition to referring to greenhouse gases, mitigation also applies to reducing emissions of other substances that have a heating effect on the climate.
- **Model (Climate model)**
  Complex computer simulation of the climate system usually including interacting simulations of the atmosphere, ocean, ice and land surface. The climate system can be represented by models of varying complexity. Climate models are developed and used at climate research institutions around the world to make projections of future climate, based on future scenarios of greenhouse gas and aerosol forcing. See also Earth system model.
- **Paris Agreement**
  The Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) was adopted on 12th December 2015 in Paris, France, at the 21st session of the Conference of the Parties (COP) to the UNFCCC. The agreement, adopted by 196 Parties to the UNFCCC, entered into force on 4th November 2016. One of the goals of the Paris Agreement is to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. Canada ratified the Paris Agree-

ment in 2016. The Paris Agreement is intended to become fully effective in 2020.

- **Permafrost**
  Permafrost is soil, rock or sediment that is frozen for more than two consecutive years. In areas not overlain by ice, it exists beneath a layer of soil, rock or sediment, which freezes and thaws annually and is called the "active layer".
- **Radiative forcing**
  The net change in the energy balance of the Earth system due to an external perturbation, measured in units of watts per square meter (W/m^2).
- **Scenario (forcing scenario, emission scenario)**
  A plausible representation of the future based on a coherent and internally consistent set of assumptions. A forcing scenario is a possible future evolution of greenhouse gas concentrations and other anthropogenic forcings. An emission scenario describes a possible future evolution of emissions of greenhouse gases, and other climate drivers. They assist in climate change analysis, including climate modelling and the assessment of impacts, adaptation, and mitigation. The likelihood of any single emissions path described in a scenario is highly uncertain.
- **Sink**
  Any process activity or mechanism that removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol from the atmosphere. For example, methane is removed from the atmosphere primarily through photochemical reactions that destroy it chemically. Carbon dioxide is removed from the atmosphere through uptake by plants during photosynthesis (a "land sink") and through dissolving in ocean water (an "ocean sink").
- **Source**
  A source is any process, activity or mechanism — natural or human — that releases greenhouse gases, an aerosol, or a precursor of a greenhouse gas or aerosol to the atmosphere.
- **Uncertainty**
  In this document, "uncertainty" is used mainly in the statistical sense, to mean quantified measures of likelihood. Uncertainty may be based on statistical analysis of observations or model results, or on expert judgment. "Uncertainty" is also used occasionally in this document to express the unreliability of projections of future events.
- **Unified modelling framework**
  In this document, this extends across ASTD the same concept as applied under the **CCCma Integrated Modelling System**. Sometimes this term is used to refer to the integration of modelling systems across the existing separate Numerical Weather Prediction (NWP) and Climate modelling systems. At one end of the spectrum, a unified modelling framework would be a loose collection of model components, with some degree on interoperability. On the other extreme, a single model configuration might be used for both NWP and climate applications, which is sometimes referred to as seamless prediction. However, a single model is likely not optimal for performance or quality given the significant scientific, technical and organizational issues associated with it.