Canadian Space-Based Atmospheric Science Community Roadmap

Prepared by the CSA's Atmospheric Science Advisory Committee
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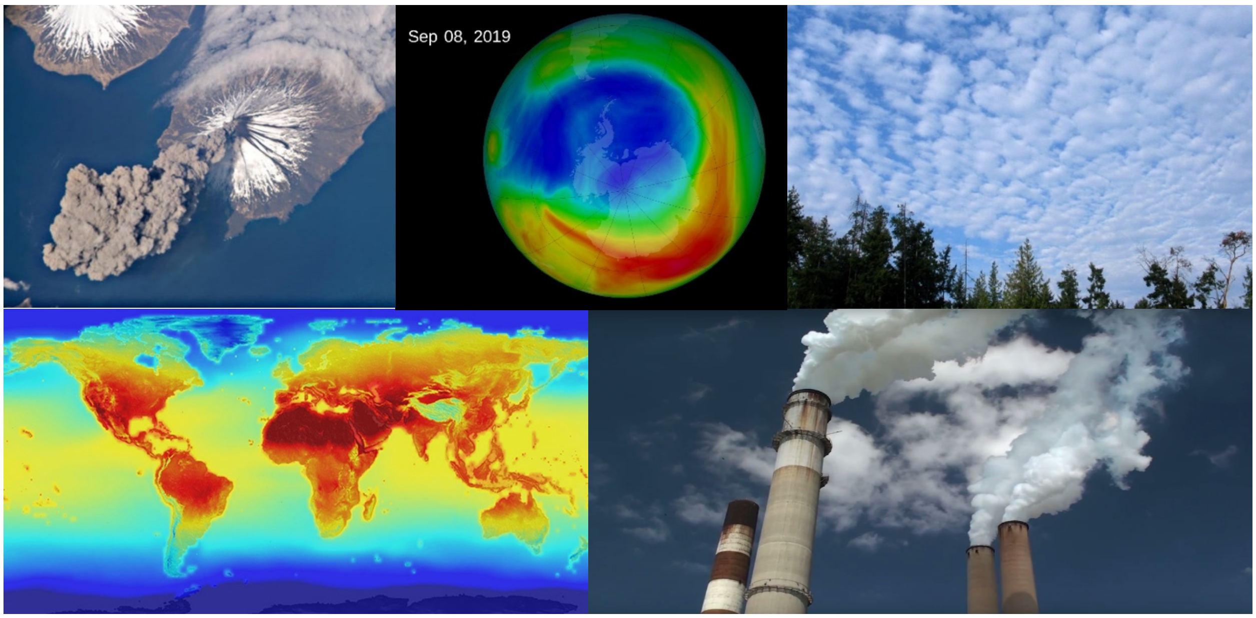


1. INTRODUCTION

Atmospheric science has been providing answers to the most pressing questions humanity has been asking for centuries: Can you explain today's weather? What will the weather be tomorrow? Will my safety, security, or my food production be compromised because of the weather? In the past, weather was considered as mostly random, but some saw emergent patterns and over time we began measuring atmospheric variables from the surface of the Earth. Through the application of these surface observations and physical principles, we began to forecast the weather. But with the dawn of the space age and the first weather satellites of the 1960s, capabilities accelerated and we have witnessed humanity's ability to observe the Earth from space, identify weather patterns, and then analyze data to calculate speed and direction of weather systems and to forecast their motions.

Today, our understanding encompasses not just the weather, but also the composition of our air and how these complex and interacting systems evolve on longer time scales, often called the "climate". With a combination of precise and sophisticated space- and ground-based measurements, powerful computational resources, and accurate quantitative numerical models, atmospheric science is now making profound discoveries about the Earth's atmosphere at a faster pace than ever before. Space-Based Earth Observation (SBEO) helps to warn humanity about major weather systems and informs society to develop mitigation strategies for millions of people. Atmospheric monitoring led to the discovery of the "ozone hole" and over time mobilized every country on the planet to eliminate ozone-depleting substances, an action that has saved millions of lives from skin cancer and cataract disease. Space-based observations detect and quantify sources of air pollution and greenhouse gases, and illustrate with surprising detail how within days these emissions circulate over continents, across the oceans and around the globe. Observations from space help us understand and predict atmospheric variables on timescales of days, years, and decades and project them centuries in to the future.

Given our country's size, varied terrains, and often harsh climate, obtaining Canada-wide measurements of many of these important atmospheric parameters is often most effective through space-based observations. Twenty years ago, the foundation of Canada's SBEO efforts was laid by developing, launching, and operating missions to study air pollution, ozone-depleting substances, and greenhouse gases. While an international space-based atmospheric observing system currently exists, from which Canada draws from for monitoring and prediction of weather, pollution, climate, and ultraviolet radiation, it is critical that Canada increase its own space capabilities to both fill observation gaps and enhance our contribution to this international data pool.

Our ability to measure and monitor atmospheric variables is increasing with use of measurement records spanning multiple decades that are now available. These extremely valuable satellite data sets enable us to carefully study the Earth's climate, monitor its changes, and communicate these changes to the world. The Secretary-General of the United Nations has declared that *Climate change is the defining issue of our time – and we are at a defining moment. We face a direct existential threat. … If we do not change course by 2020, we risk missing the point where we can avoid runaway climate change, with disastrous consequences for people and all the natural systems that sustain us* [1]. The Government of Canada has also documented that *climate change continues to be the most pressing challenge we face. From the increased frequency and severity of extreme weather events, to the thawing of the permafrost, Canadians are paying for the cost of climate change* [2]. In response, Canada is investing in new climate change policies to help Canadians increase their resiliency to a changing climate.

To support this endeavour, Canada now needs new investments in Canadian-led and international partnership missions to monitor our vast territory, the second largest in the world, to acquire unique atmospheric data that can only be measured from space, and to continue applying such data to future numerical weather prediction and climate projection models.

[1] UN Secretary-General's Remarks on Climate Change, UN Headquarters, 10 September 2018.
[2] Environment and Climate Change Canada, 2019–20 Departmental Plan, En1-65E-PDF, 2019.

2. ADVANCING CANADIAN LEGISLATION AND PRIORITIES

Humanity has grown dependent on the study of the Earth's atmosphere because it is critical to our livelihood and human health. Governments have responded by setting priorities appropriate to protecting their people and environment, and have enacted laws that enshrine these priorities. **Governments, nationally and internationally, clearly understand that the atmosphere is essential for the health and success of humanity in all its dimensions.**

The enacted laws in dozens of countries, including Canada, regulate the quality of air that we breathe, protect us from harmful gases and radiation, and limit the buildup of gases generated by human activity that threaten us. The many environmental laws, legally-binding treaties and government documents relevant to Canadian and space activities have been reviewed and are summarized here to link their needs and priorities to the study of atmospheric science from space in Canada.

National Exercises

A New Space Strategy for Canada: Canada's 2019 space strategy makes the case for Canada's investment in space, articulates Canada's broad vision for space, and identifies five strategic vision delivery mechanisms. The Government of Canada recognizes that SBEO and scientific data, including atmospheric measurements, are essential for clean growth and monitoring the health of the planet and that Canada's existing atmospheric science missions have been foundational to the global effort to combat climate change. It also recognizes that the unique data collected from Canada's space assets enable the Government to make evidence-based decisions that keep Canadians safe, and monitor and protect our environment.

Canadian Environmental Protection Act (CEPA): CEPA is the primary element of Canada's legislative framework for protecting the Canadian environment and its relation to human health. This law prevents and manages risks to the environment and human health posed by toxic and harmful substances as well as other sources of pollution. Under the Act, Canada is to establish, operate and maintain a system for monitoring environmental quality and conduct research on pollution prevention and the effects of pollution on environmental quality.

Pan Canadian Framework on Clean Growth and Climate Change: This is Canada's plan – developed with the provinces, territories and Indigenous peoples – to grow the economy while reducing greenhouse gas emissions and building resilience to adapt to a changing climate. It will require taking action on long-lived greenhouse gases such as carbon dioxide and short-lived climate pollutants such as methane, hydrofluorocarbons, and black carbon. A collaborative, science-based approach will be used to inform Canada's future targets, as they increase in stringency as required by the UN Paris Agreement. Governments also recognize the unique circumstances of the North, including the disproportionate impacts of climate change.

Space-Based Earth Observation (SBEO) Vision for the Future: This Government of Canada initiative recognizes the important role that SBEO plays in collecting the environmental data required for Canada to meet its needs and priorities. An interdepartmental task force, co-led by the Canadian Space Agency (CSA) and Environment and Climate Change Canada (ECCC), has recently created a vision for the future of SBEO with a value chain framework and highlights key areas where SBEO has the potential to deliver a faster, more accurate, or more cost-effective approach to providing this critical environmental information. There are six key areas identified, including Healthy Canadians and Climate Change Action and Resilience.

<u>**International Exercises**</u>

United Nations Montreal Protocol: In conjunction with the *Vienna Convention for the Protection of the Ozone Layer*, this legally-binding treaty established in Montreal in 1987 regulates the production and consumption of almost 100 substances that deplete the ozone layer in all 197 countries around the world, including Canada. Over the past two decades, Canada has fulfilled its commitments under the Vienna Convention to monitor and improve our understanding of the ozone layer by establishing, developing, launching and operating Canadian and international partnership satellite missions as well as providing recognized high-quality SBEO data to the quadrennial ozone assessment reports.

United Nations Framework Convention on Climate Change (UNFCCC): Ratified by 197 countries and adopted in 1992, the ultimate objective of the UNFCCC is to stabilize greenhouse gas concentrations at a level that would prevent dangerous human-caused interference with the climate system. The *Intergovernmental Panel on Climate Change* (IPCC) is the leading UN body that assesses the science related to climate change. Founded in 1988, it provides the scientific evidence to help policy makers make decisions on reducing our impact on the climate and adapting to climate change.

United Nations Paris Agreement: This 2015 treaty was signed by 195 countries and aims to fight climate change by strengthening efforts to limit global temperature rise to well below 2°C. Although each party's pledged emission reductions are not legally-binding, they are legally bound to track their progress under an enhanced transparency framework of monitoring, reporting and verification.

Canada-US Air Quality Agreement: This 1991 bilateral legal treaty regulates emissions related to wind-driven transboundary air pollution between the two nations that can cause significant harm to human health as well as to natural resources of vital environmental, cultural, and economic importance. This agreement requires monitoring of air pollutants such as ground-level ozone and other compounds related to smog and acid deposition including nitrogen dioxide, sulfur dioxide, and carbon monoxide over the North American continent.

United Nations Gothenburg Protocol: Canada is a signatory of this legally binding treaty that aims to control and reduce criteria air pollutants, including sulfur dioxide, nitrogen dioxide and tropospheric ozone, in 18 countries in Europe and North America. Through this 1999 protocol, Canada continues to actively contribute to the advancement of scientific policy.

Funding new satellite missions is an effective way for Canada to quantitatively monitor relevant atmospheric trace gases to report on their production and emission as required by these laws, treaties, agreements and priorities.

3. CANADA'S ATMOSPHERIC SCIENCE RESEARCH COMMUNITY

Canada possesses a wide and diverse community of researchers in atmospheric science that span all provinces and come from academia, government and the private sector. This includes over 200 academic researchers from over 25 research institutions, while the federal government departments of ECCC, Natural Resources (NRCan), and the National Research Council (NRC) are home to over 150 atmospheric research scientists. The Atmospheric Science and Technology Directorate, within ECCC, and specifically the Climate, Meteorological, and Air Quality Research Divisions, employs the largest contingent of atmospheric science-related researchers within the government, with significant research contributions from NRC and NRCan in areas related to airborne activities, climate modeling, wildland fire modelling, and extreme weather events. The academic and government efforts are supported by industrial research and development activities in both large corporations and small- and medium-sized enterprises located across Canada.

Collectively, the research of these Canadian scientists spans virtually all the atmospheric science disciplines including: weather and weather forecasting, aerosols and clouds, stratospheric ozone and ozone-depleting substances, greenhouse gases, air pollution, as well as studies of sinks, trends, and ambient concentrations of atmospheric constituents. Additional areas of research are long-range transport, Earth's radiative budget, instrumentation and technology development, laboratory studies, space-based measurements, field research using a variety of ground-based and suborbital platforms, and Earth-system modeling at all scales.

The Canadian atmospheric science community contributes research and development to all segments of the SBEO value chain, with many researchers working across more than one segment. These contributions range from conceiving and developing new missions and instrumentation; to seeing them through to launch and operations; to processing measurements, calibrating instrumentation and validating data products; and to utilizing the output to generate new discoveries and services. While the largest number of researchers work in the downstream segment, there are significant numbers of researchers in the atmospheric science community who work on the upstream and midstream segments of the value chain.

In all, Canada has a large professional weather and climate research capacity with world-class expertise in the full range of atmospheric sciences. Canadian atmospheric scientists perform fundamental research and advanced technological development to address both emerging and long-standing science questions. They are leaders on the international stage, and address the needs of Canadians. **This community further supports emergency management, mitigation, environmental and human health studies, ultimately contributing to the safety of human life and the prevention of economic losses from extreme weather events and climate change.**

4. CANADIAN ATMOSPHERIC SCIENCE THEMES

Each of the atmospheric research themes described here impact on a wide variety of societal concerns and have strong scientific linkages that interweave to create an intricate tapestry. This applies across Canada and particularly in the Arctic. **Atmospheric issues impact Canadians' basic needs including food, transport, security, water resources, weather information, and health**. This section summarizes the major scientific challenges and issues being addressed in atmospheric science today.

Aerosols: Aerosols are tiny airborne particles of condensed material in suspension in the air. Their effect on air quality, health, and visibility, on the one hand, and on climate from solar radiation absorption and scattering, on the other hand, are of concern to the atmospheric community. Submicron-size particles are deposited deeply in the respiratory system and are associated with a variety of negative health outcomes, including significant hospitalizations in Canada. They are linked intimately to gaseous compounds in the air via the process known as gas-to-particle conversion. Combustion soot and windblown materials such as soil dust, sea salt, volatile organics and pollens are some of the primary sources. SBEO applied to aerosol observations aims to provide information on their concentration, composition, size, and sources. Modern satellites are on a path to improve aerosol detection, identification and concentration quantification from their sources to dispersion on regional to planetary scales.

Air Quality: Air quality refers to atmospheric composition in the context of air pollution, including chemically active trace gases, aerosols (see above), and their precursors. Pollutants such as ground-level ozone, oxides of nitrogen and sulphur, volatile organic compounds, ammonia (and many others) make up a very small fraction (<0.1%) of air with concentrations on the order of parts per million, billion, or even trillion, yet they control the chemistry of the lower atmosphere. These pollutants are ingredients in smog, which is detrimental to human health, are damaging to crops, and have adverse effects on the environment through eutrophication and acidification of water and soils. Complex computer models have been used extensively to forecast current and future air quality in much the same way as for weather. The future of operational air quality forecasting, like weather, lies in the assimilation of near-real time satellite air quality observations in order to improve forecasts.

Arctic: Canada is the custodian of a large part of the Arctic, a region that serves as a nexus for all the other themes discussed here. While this region is remote, observations of the Arctic are essential due to its fragile ecosystems and extremely sensitive climate with temperature increases three times the global average. Understanding the potential for future Arctic ozone depletion, the impact of increased resource exploration and development, the significance of permafrost thaw on the global carbon cycle, and the implications of the intercontinental transport of air pollution to the Arctic, are some examples of cross-cutting science issues. Likewise, applied Arctic research deals with improving weather forecasts in a region with harsh conditions and fewer observations than lower latitudes, and with understanding the impact of Arctic storm generation on mid-latitude weather in Canada and globally. To address these challenges, it is critical for Canada to develop and maintain a multi-platform observational capability including observing stations and SBEO solutions that specifically target the Arctic atmosphere.

Carbon Cycle: Earth's natural carbon cycle involves the exchange of carbon between the land, atmosphere and ocean. Anthropogenic activities have perturbed the carbon cycle by releasing carbon from reservoirs to the atmosphere, predominantly by burning of fossil fuels and land use change. Excess atmospheric carbon, mostly as carbon dioxide and methane, has caused a shift in the radiative balance resulting in climate change. Satellite observations of these atmospheric gases can help us to track emissions and understand their processes and drivers in greater detail. A major focus for future missions is improving coverage of carbon cycle measurements in northern regions to enable better monitoring and management of carbon in a changing climate and to support international agreements.

Climate: Climate change has made atmospheric sciences more relevant than ever to human society. Global warming is fueled by an imbalance in radiative energy and modulated by various feedback mechanisms that modify atmospheric temperature, composition, and circulation patterns. For instance, the high-latitude climate is particularly variable due to the amplifying ice-albedo feedback, leading to increased warming (Arctic amplification). Using measurements from space, atmospheric scientists are challenged to monitor the radiative forcing and feedback agents that drive climate change, such as greenhouse gases, aerosols, clouds, wind patterns and circulation, and to understand the interactions between them that shape the climate at both global and regional scales.

Clouds: Clouds are among the most difficult phenomena to understand and to parameterize in atmospheric models. The prime reason for this problem is what scientists would call their non-linear response to environmental changes. Clouds form when water condenses and evaporates in short times and spaces making them hard to model accurately. Yet, they are the most significant factor in modulating the weather and climate, and the greatest source of uncertainty in climate projection. Clouds are one of the leading research avenues in atmospheric science that require space instruments at the forefront of technology.

Ozone: Stratospheric ozone filters ultraviolet radiation, protecting life at the surface. In the wake of the discovery of the ozone hole and more general decline in ozone at mid-latitudes, treaties were implemented banning many known ozone-destroying substances (the Montreal Protocol and its amendments). While much has been learned in the past several decades, it remains imperative to continue to observe ozone and ozone-related compounds. While stratospheric ozone in the mid-latitudes is expected to be increasing, there is mixed evidence as to whether and when a statistically significant increase can be detected. Furthermore, the recent detection of new emissions of banned ozone-destroying substances combined with the 2020 "Arctic ozone hole" event, further highlight this. Satellite remote sensing remains the only feasible method for continuous ozone monitoring, and can provide a detailed three-dimensional picture of this critical gas and the compounds that are involved in its atmospheric processes.

Weather: Weather forecasting is a core application of atmospheric sciences and its accuracy represents the level of our understanding of the physical processes involved. The modern forecast relies on complex global and regional numerical models to generate the variable parameters of interest such as temperature, precipitation, surface wind and air quality, up to 12 days into the future. Satellite observations have been a cornerstone in making the forecasts better, by providing more accurate initial conditions for the model integration via data assimilation and by providing observational ground truth for validating the model physics. For example, there are challenges predicting Arctic precipitation that are critical to address and require improved observations. Atmospheric scientists have persistently pursued how to make more complete and more effective use of satellite data to improve forecasts, especially in critical regions such as the surface boundary layer (e.g., where we live) and the tropopause region.

5. RESEARCH STRENGTHS IN CANADA

Canada has a proud tradition of space activities. **Over the last 60 years, Canada and Canadians have developed many strengths associated with space activities. These are in several areas that are competitive and are leading the international community.**

Space missions: Canada's first space mission, Alouette-1 launched in 1962, studied the upper reaches of the Earth atmosphere. Since then, many space missions developed by Canadian scientists and engineers have probed the entire atmosphere. Those currently operating are reviewed here. In December 1999, Canada launched the *Measurement of Pollution in the Troposphere (MOPITT onboard the NASA Terra Satellite, still operational 20 years later)*. MOPITT is the first space-borne instrument to continuously map global carbon monoxide and is now the longest continuously-running space mission in Canadian history. MOPITT led to multiple discoveries in understanding air pollution and its transport around the Earth. In February 2001, the *Optical Spectrograph and InfraRed Imaging System (OSIRIS, still operational onboard the Swedish Odin satellite)* mission was launched to measure atmospheric profiles of ozone, nitrogen dioxide and aerosols in the stratosphere and mesosphere. This collaboration, among other novel products, has produced the longest-running, currently operational ozone data record from space. Canada's *Atmospheric Chemistry Experiment (ACE) or SCISAT (with the Fourier Transform Spectrometer (ACE-FTS) and the Measurement of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation (MAESTRO) instrument)* mission was launched in August 2003 and still continues to measure more gases than any other satellite mission. Using solar occultation, SCISAT measures vertical profiles of trace gases including ozone, ozone-depleting substances, air pollutants and greenhouse gases from the upper troposphere to thermosphere. Its data continue to be used for a wide range of studies in atmospheric science. Finally, NASA's *CloudSat mission (with a cloud profiling radar and to which Canada contributed the Extended Interaction Klystrons and a radio frequency electronics subsystem)* was launched as part of the A-Train in April 2006 to measure the three-dimensional profile of clouds. CloudSat has revealed the quantity of ice and water contained in clouds globally and determined how clouds heat or cool the atmosphere.

Instruments and Technology: Canadian aerospace companies have conceptualized, designed, built, tested, and launched multiple sub-systems, instruments, and satellites. Many of these companies are involved in space activities for atmospheric science. Here are two examples: Canadian development of Fourier Transform Spectrometer (FTS) instruments began with our early balloon programs and were critical to the development of the ACE-FTS on SCISAT. Since then, this interferometer technology has been developed, leveraged, and exported to the U.S., Japan, and China for use in more than five new space missions. Canadian industry has also developed a capacity to produce high-quality and long-duration mechanisms required for space instrument development. The multiple mechanisms embedded into MOPITT, including scanners, choppers, pressure modulated cells, and cryogenic coolers, demonstrate this. Since launch, these have now undergone billions of cycles, rotations, and scans and are used as examples of the longest running space mechanisms in orbit to date – a singular achievement for Canada.

Infrastructure: In addition to the existing Canadian space assets operating today, Canada has facilities and instruments that support a variety of space projects and programs over their entire life cycle. A variety of atmospheric environmental testing chambers continue to operate across Canada, including those at the University of Toronto, York University, University of Saskatchewan, CSA's David Florida Laboratories, and at several companies. These facilities are crucial in developing and testing space and suborbital systems prior to launch. The Polar Environment Atmospheric Research Laboratory (PEARL) in Eureka, Nunavut (80°N) is a unique facility to calibrate and validate satellite data. PEARL is Canada's most comprehensive atmospheric measurement site in the high Arctic, and provides test-beds for instrumentation, hosts the annual satellite validation campaign for both the SCISAT and OSIRIS missions, and is critical in training the next generation of scientists and engineers in atmospheric physics, chemistry, and climate change. Multiple other Canadian ground-based facilities run by academia and government contribute to essential validation networks used for Canadian and international space missions, to ensure the highest quality atmospheric data for science applications.

Data Production: Data production and processing are a vital link between the hardware used to measure the atmosphere and the products or services required by and for society. Because of the longevity of its existing atmospheric remote sensing space assets, Canada has world-class experience in atmospheric data production and processing in multiple academic institutions and within the Government of Canada (e.g., ECCC and NRCan). These institutions have experts with many decades of experience in data production, processing, and radiative transfer model and algorithm development using large-scale computational facilities. This body of work takes existing ground- and space-based measurements of atmospheric constituents and creates new algorithms to produce new data sets with unique characteristics relevant for the Canadian territory.

Modeling and Assimilation: Atmospheric modeling and data assimilation is another strength of Canada, both in academia and in government. ECCC operates world-class weather forecasting models, and numerical weather prediction systems and academic research explores ways to improve them. ECCC and academia both develop climate models that capture multiple chemical processes related to the atmosphere and other components of the Earth system to make long-term climate predictions. Chemical transport modeling leverages developments in both of the above areas to model the transport of greenhouse gases, or physical and chemical changes to pollutants in the atmosphere. These systems often use space-based measurements to discover new physical or chemical processes in the atmosphere and can address uniquely Canadian issues of interest. This Canadian community includes world-class experts and international authorities in the complex theories and critical techniques that are used to model and advance our understanding of the atmosphere and climate over Canada and around the world.

Suborbital Research Platforms: In the early 1980s, balloon flights were conducted from Canada by ECCC and NRC to investigate ozone and ozone depletion. From 1998 to 2004, Canada launched four *Middle Atmosphere Nitrogen Trend Assessment (MANTRA)* balloon missions from Saskatchewan, with a suite of atmospheric instruments to measure vertical profiles of stratospheric ozone, and of nitrogen and chlorine compounds involved in ozone chemistry.

Today, suborbital platforms are an essential part of the upstream and midstream SBEO activities that include supporting proof-of-concept studies, and subsequent technology development before launch and calibration and validation activities after launch (as described in the next section). Suborbital platforms also provide a complementary downstream data set to space-based ones for answering specific science questions through carefully designed experiments targeting geographical regions or environmental conditions. Canada has established a national balloon launch facility in Timmins, Ontario, in collaboration with the French space agency (CNES). Here, balloon launches in Canada using French launch and gondola equipment and Canadian mission concept and prototype validation instruments occur on a regular basis and have contributed to sustaining the atmospheric science capacity in Canada.

Canada also has over 50 years of airborne experimentation using aircraft in atmospheric studies. Canadian researchers from both government and academia are world leaders in airborne measurements and have developed unique aircraft capabilities for supporting SBEO activities. These capabilities include aircraft owned and operated by the NRC Flight Research Laboratory and various Unmanned Aerial Vehicles. The unique Canadian research aircraft capabilities and our cold weather and climate attract international agencies and researchers to team up with Canadian scientists in SBEO activities. A recent example includes ECCC and NRC researchers collaborating with various international partners using the extensive capabilities of the NRC Convair-580 aircraft.

Satellite and Instrument Operations: Canadian industry has been involved in the day-to-day satellite operations of many Canadian assets, including SCISAT. It has developed the operational capacity to command and control the satellite, to resolve and optimize telemetry downlinks for scientific and engineering data, to automate the analysis of satellite engineering data, and to test and implement anomaly resolution protocols. It has worked in collaboration with the Canadian academic sector to successfully operate its scientific instruments and increase the datalink capacity of its atmospheric measurements. In addition, Canadian academia has also been involved in satellite instrument operations that now spans over two decades and have a depth of experience to support on-going and future missions. University scientists have developed the operational capability to design, schedule, and/or implement commands; to develop automated procedures to analyze satellite instrument data; and to carefully monitor instrument performance and resolve anomalies.

Personnel: Interwoven in each area of strength is its people. Canada has a large cadre of scientists, engineers, and technicians who are highly trained and well-experienced in the design, development, launch, operations, and data processing of atmospheric science missions. These professionals take space-based atmospheric measurements and innovate with a continual flow of new ideas to develop new and improved products for use in Canadian society. In addition, they support these satellite measurements with ground-based and suborbital flights for calibration, validation, science discovery, and technical development and with atmospheric modelling for climate and weather applications and development. The breadth and depth of experience gained by Canadian experts from all the above areas is a priceless Canadian asset. This community is ready and able to apply these foundational capabilities to a new generation of Canadian satellite missions already designed to address the most urgent atmospheric science problems of our time.

6. ATMOSPHERIC SCIENCES ROADMAP

The Canadian atmospheric sciences roadmap must leverage Canada's past successes, strengths and emerging capabilities to address the priorities of the scientific community and the Government of Canada. Furthermore, the roadmap charts the course for building Canadian capacity in key areas through targeted activities and investment.

The components of the atmospheric sciences roadmap will be discussed in the context of the Earth Observation Value Chain framework put forward by the Government of Canada's Interdepartmental Space-Based Earth Observation (SBEO) Task Force. This describes the process of generating and using Earth Observation data and is defined in terms of ***Upstream (Data Capture)*** – ***Midstream (Data Handling)*** – ***Downstream (Data Exploitation)*** segments. The value chain begins with ***Drivers***, or ***Data Needs***, which come from government priorities, departmental mandates and scientific analyses. This value chain then delivers data to ***End Users*** in government, academia, industry and the general public resulting in ***Data Use***. **The Canadian atmospheric science community actively contributes to all components of the SBEO Value Chain and the community is comprised of both drivers and end users from academia, government, and industry.**

Upstream – Data Capture

Within this segment, the space infrastructure and international partnerships to provide SBEO data are included. In the next decade, there must be regular, transparent, and open processes for selecting and launching missions and instruments that have been developed over the last decade and for entraining new technologies and concepts in the development process to produce the ideas needed for the following decade.

For the atmospheric science community, opportunities to develop new missions, concepts and instruments to orbital missions must be balanced with operating current missions that are continuing to produce excellent data sets. In atmospheric science, the longevity of the data set increases its worth exponentially. Also, it is critical to have mechanisms in place to commit credibly to international partnerships and contributions as these can be a cost-effective way for Canada to participate in atmospheric science missions. These three components are discussed below.

- **New Missions for Atmospheric Science:** The CSA is currently funding two atmospheric mission concepts: the Atmospheric Imaging Mission for Northern Regions (AIM-North) / Arctic Observing Mission (AOM) and the Canadian contribution to the NASA Aerosols, Clouds, Convection and Precipitation (A-CCP) mission studies. (Details of concepts are found in the Appendix). As well, they have recently funded development for the Chemical and Aerosol Sounding Satellite (CASS), strongly building on Canadian heritage and expertise. These missions are the priorities for the Canadian atmospheric science community and address the themes listed above. Launching these space missions will enable Canada to address its own unique national priorities in greenhouse gas monitoring, air quality and pollution measurement, ozone recovery assessment, climate and radiation studies, and weather forecasting over its full territory. It is important for CSA to move these priority missions forward for flight.
- **Continuing Missions:** CSA currently has three on-going atmospheric science missions producing atmospheric remote sounding data that are exceedingly well utilized within Canada and internationally. SCISAT/ACE, OSIRIS and MOPITT are essential to Canada's ability to maintain the critical mass of scientific and technical expertise within our community for

generating and utilizing space-based data and to demonstrate Canada's ability to participate with the international community. Continuing missions must be supported for as long as the data products continue to be of high quality and have significant impact within the Canadian and international scientific and policy communities.

- **International Opportunities:** With Canada being a co-operating member of ESA, currently considering participation in Copernicus and having a history of collaboration with NASA and other space agencies, international partnerships or other opportunities will continue to represent a key component of Canada's future atmospheric science efforts from space. While potential missions are exploring international partnership scenarios, Canada currently lacks a systematic framework to evaluate and facilitate international mission partnerships and opportunities. A both dedicated opportunity evaluation process and a reliable funding mechanism need to be developed to enable Canadian participation in international missions.

To support the development of future atmospheric science innovations for Canada in the Upstream component, a range of activities are required and must be supported through regular, transparent and open processes. These processes must enable ideas to be matured through technology and science development steps that are separate from a mission opportunity. This will ensure that instruments are being readied that can be proposed as credible contributions to international missions. Funding for the areas listed below is required to develop the next generation of Canadian and international partner missions for the coming decades. Examples of instruments and missions that have been proposed for development are listed in the Appendix.

- **Instrument and Mission Concept Studies:** These studies are critical to getting advanced instrument or other space technologies integrated into national or international space missions. Over the past decade, the Canadian atmospheric science community has developed a number of new mission concepts spanning microsatellites, science missions and even operational missions to address government needs.
- **Technology Development and Testing:** This is an activity critical to advancing the technology readiness of SBEO instruments and systems, by developing and advancing new technologies or improving existing technologies within Canada. Over the past decade, new instruments and technologies to measure gases, aerosols and high-altitude clouds with improved capabilities have been tested in the laboratory, on suborbital platforms and during ground-based measurement campaigns.
- **Capability Demonstration:** This is a crucial activity to take newly developed space instrument technologies and test them in space-like settings to further their readiness. Research platforms that represent aspects of the harsh environment of space and enable the demonstration of observations include aircraft, balloons, suborbital rockets, and very cold and remote ground-based locations in the high Arctic.
- **Data Retrieval Development and Science Demonstration:** For these newly developed technologies, this important activity advances Canadian capabilities and science readiness through creating new algorithms, developing new operational procedures, and producing new atmospheric data products useful for Canada's atmospheric science community. These developments enable new concepts and technologies to move forward for use in a new mission.
- **Mission End-to-End Modelling and Simulations:** These activities are critical for new mission development by simulating the expected performance of the instruments and systems and by assessing the scientific value and utility of the proposed data products. These studies are also crucial for optimizing satellite observation and instrument design to ensure that these meet mission objectives.

Midstream – Data Handling
This component covers **Acquiring and Collecting** data as well as **Enabling Access** to data. For atmospheric science data, these activities include producing data sets from instrument outputs, calibrating instruments and systems, validating data products, and making data available to the user community. These are all critical components of an atmospheric science mission and must be funded consistently throughout the life of the mission. In particular, calibration and validation activities often "fall through the cracks" because it is assumed that capabilities and facilities will exist without providing any mission support. Funding for the activities listed below is essential to ensure that Canada gets the most for its investment in atmospheric science missions in the coming decade.

- **Data Processing:** This activity takes the raw measurements from the satellite (typically, spectral data) and applies sophisticated analysis techniques to retrieve atmospheric parameters such as gas concentrations, aerosol characteristics, and temperature. Development of retrieval codes performed by academia and government is critical for missions. It is an on-going activity throughout a mission and continues many years beyond a mission's lifetime. Reprocessing is required for changes in the on-orbit instruments, changes in the retrieval framework, new priorities for science and government, and new science using existing and on-going data sets. On-going support for data processing activities is essential: to leverage the original investment in the upstream to produce improvements to key data sets; to develop new and unanticipated data products; and to enable the generation of new atmospheric knowledge for Canada.
- **Pre-launch and On-orbit Calibration:** These activities are crucial to ensuring that the operation and outputs of the satellite instruments are as well characterized as possible. Support is required for measurement campaigns using laboratory, ground-based and suborbital instrumentation in conjunction with engineering and flight hardware. Regular calibration activities provide essential input data for satellite missions and enable optimum operations.
- **Data Set Validation:** This activity assesses the quality of satellite data products and is essential to achieve high quality data from any mission. It is undertaken through comparisons of satellite data with well-characterized data sets from ground-based, balloon-borne, and aircraft instruments. It is an on-going activity throughout a mission and continues beyond its lifetime to ensure data quality. To have the crucial data needed to validate Canada's current and future atmospheric science satellites, funding is required to conduct dedicated ground-based and suborbital validation campaigns throughout the mission. In addition, a funding mechanism is needed to build and sustain a network of strategic ground instruments for this purpose, so that well-calibrated systems are operational when needed for validation.
- **Validation Support for International Missions:** All Canadian missions depend on data from international collaborators to conduct global validation assessments. In return, Canadian measurements are used to validate international missions over Canada. These international programs require national funding to support all validation activities including collection of data, analysis and dissemination. Because the exchange of data and expertise is critical for both new and continuing Canadian and international missions, validation activities must be supported.

Downstream – Data Exploitation
In this final component, two aspects are included: **Exploitation** of the data and **Getting More from our Data**. In the area of Exploitation, data analysis and modeling activities must be supported to expand Canada's utilization of space-based data for Earth System monitoring and prediction. To Get More from our Data, the atmospheric science community contributes significantly to developing the workforce of the future by training highly qualified personnel (HQP) and to enabling

partners in all sectors to add value and innovate. These activities and personnel must be supported and sustained to ensure continuity of scientific expertise and effective exploitation of SBEO data.

- **Scientific Discovery and Data Analysis:** This activity advances the understanding of physical and chemical processes in the atmosphere as well as Earth-surface processes that affect atmospheric composition. Working individually and together, academic and government researchers use space-based data to discover new information about the atmosphere and its interactions. These researchers employ analytical techniques, such as big data and machine learning (artificial intelligence), to add value and gain insight into the Earth System. In addition, they transfer new knowledge to government where it improves air quality, climate and other environmental prediction systems and services. Support of data analysis activities must continue over the next decade to provide the scientific knowledge, data, applications and tools needed to enable Canadian policies, programs and services to help provide a clean, safe and sustainable environment.
- **Data Assimilation Capacity:** Canadian capacity for modelling and assimilation of satellite data is essential to obtaining the greatest return from any space mission investment. By optimally combining observations with numerical models, data assimilation of atmospheric composition is able to derive new insights into Earth System processes and improve our predictive capability for atmospheric chemistry. This must be developed through leveraging existing capabilities in the Government of Canada to implement a more comprehensive and coordinated chemical data assimilation science facility that will contribute to developing weather and air quality prediction and warning systems, and contribute to characterize pollutant and greenhouse gas sources, sinks, and trends. Support is required to develop the full potential of the data assimilation capability and community in Canada**.**
- **Earth System Model Development:** This activity enables partnerships between academia and government to further the development of Canada's Earth System Models. These are climate models that simulate whole Earth system including the atmosphere, ocean, ice, land and other components and their interactions. Satellite data are critical for evaluating the performance of Earth System Models and Canadian data sets have been used extensively for this purpose in international assessments. Mechanisms must be developed and funded to enable the academic community to participate more actively with government in development, improvement, assessment, and utilization of the Canadian Earth System Models including shared-computing infrastructure.
- **Training the Next Generation of Scientists and Engineers:** The Canadian workforce in space-based atmospheric science must be bolstered and sustained over time. Over the past decade, this activity has been focused on working with suborbital and remote field research platforms (aircraft, balloons, high Arctic research stations) and actively contributing to all mission aspects that would also occur for a typical small space mission (concept study; design and development; assembly; integration; testing; launch; flight operations; calibration; validation, and data analysis). This has led to testing new instruments, components and validation systems on balloon flights, airborne campaigns, and in the Arctic. As a seed for human and technological infrastructure, programs that support training and technology development must continue. However, these two goals need to be separated to enable training that can focus on all parts of the SBEO value chain and not only on technology development. This activity must be supported with a budget that is sufficient for the size of the space science community and the scale of activities that they want to undertake. Over the past five years, the maximum grant levels in this area have decreased steadily (by 40%) and have thereby limited the training and development that can be undertaken by the community. To fully realize the benefits of Canadian

investment in space-based atmospheric science, training the next generation of scientists and engineers across the full spectrum of activities within the SBEO value chain must be sustained at a level to enable the community's objectives.

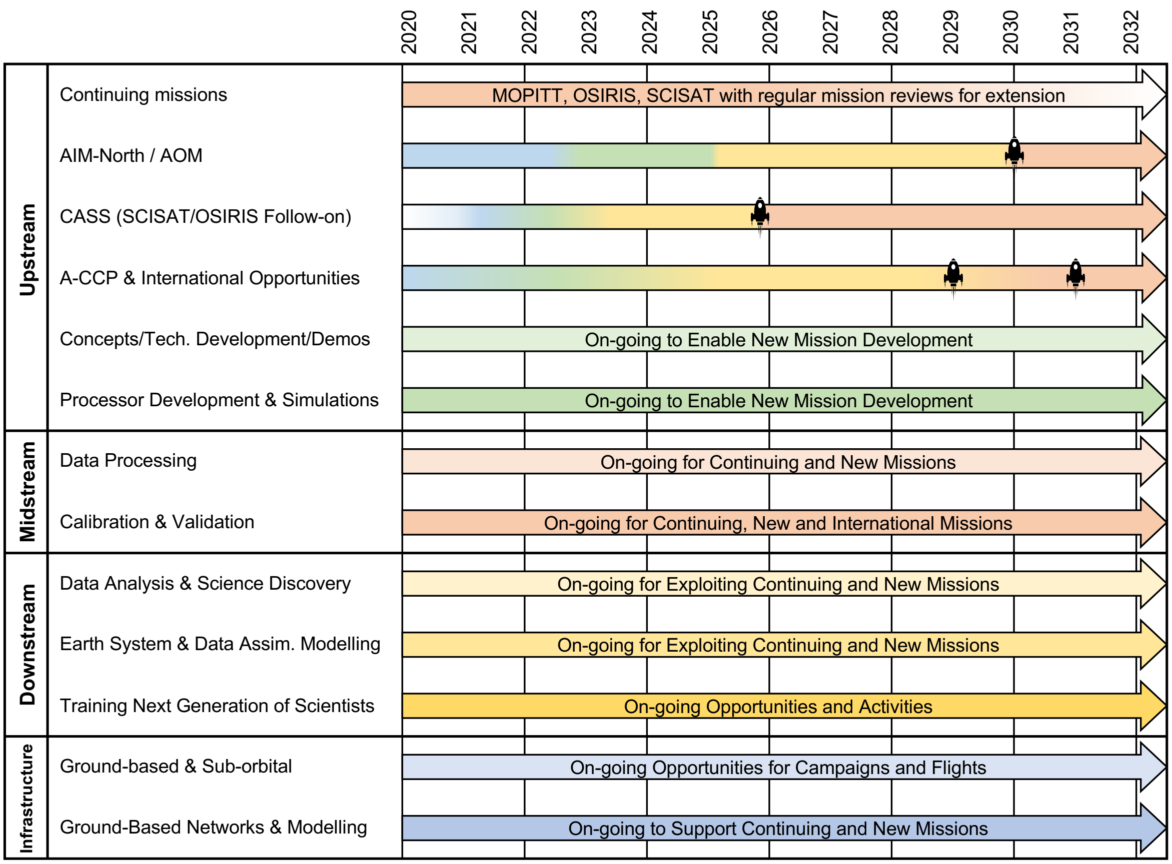
Essential Infrastructure

In order to create, analyze and add value to high-quality space-based data sets, the atmospheric community has identified the following science "on-ground capacity" that must be in place to support atmospheric science space missions. These items are in addition to the traditional ground infrastructure necessary for satellite data reception such as ground antenna receiving stations, data acquisition, and data reception services. While these are not hardware in orbit, this science infrastructure, and funding to utilize it, is essential to getting the most from the investments that Canada makes in space.

This essential infrastructure requires long-term, stable funding made available through regular, transparent and open calls and directed activities to build and sustain it. This must include support for all components of the infrastructure including personnel (not just trainees), field costs, travel, hardware, computer systems and site operation costs (e.g., electricity, communications). Too often funding has to be put together from a patchwork of different sources to make a program happen and this can lead to gaps in capacity when one funding source ends without another source that can contribute. The following essential infrastructure must be funded to support the development, generation and exploitation of Canadian SBEO data sets as well as foster the next generation of highly qualified personnel. Two proposed infrastructure concepts are listed in the Appendix.

- **Suborbital Flight Opportunities:** Suborbital flights are a vital component of the upstream, midstream and downstream segments of the SBEO value chain, as noted above. A continuing program of regular calls for suborbital flights is crucial to ensure access to this infrastructure. This must also include the flexibility to enable responses to urgent international opportunities.
- **Ground-based Network for Validation:** Ground-based validation instruments provide the essential data needed in the midstream to ensure the quality of SBEO data sets and utilized in the downstream to support data exploitation. This includes Arctic stations, such as PEARL, and strategically-located measurement sites that span the Canadian landmass. Support must be provided to ensure that these long-term validation sites are equipped and continuously operational to meet the needs of Canadian and international partnership missions.
- **Campaign Funding Opportunities:** As described above, dedicated ground-based measurement campaigns are required for technology demonstration and advancement (upstream), hardware calibration and data product validation (midstream) and science discovery and training (downstream). It is critical that a program be funded to ensure that these activities can be undertaken to support mission development, data production and knowledge generation.
- **Numerical Modelling and Assimilation:** Earth System modelling and data assimilation infrastructure is critical to all of the components of the SBEO value chain. Support is required to build up and maintain the modelling capacity in Canada to achieve our objectives in high quality satellite design and development, chemical measurement, instrument operation, data product and service development, forecast capability and science output. This could be enabled through development of a centre of expertise focused on different modelling techniques as a partnership between academic and government scientists.

The figure below summarizes the atmospheric science community roadmap as a timeline for the next decade and beyond. Activities are grouped by SBEO value chain segment. The timelines shown for the new atmospheric missions are based on current best estimates (to give estimates of development time required for each mission), with projected launch dates of 2030 for AIM-North/AOM, late 2025 for CASS, and 2029 and 2031 for the two A-CCP platforms. The projected launch dates are indicated by the rocket symbols. The colour gradations used for the new missions correspond to estimates for the phases of mission development through Phase 0 (blue), Phase A (green), Phase B-C-D (yellow), and Phase E operations (orange).



7. CONTRIBUTION TO NATIONAL OUTCOMES

Given the above activities in the past and new activities to be initiated, a number of contributions from the sector to Canadian society and the global enterprise can be expected. These are enumerated in the tables below.

Outcome:	**Space or near-space data are obtained and available for users**
Indicators:	Production of high-quality Canadian satellite (or near-space) data; Number of research institutions using data from Canadian satellite science missions; Number of peer-reviewed scientific journal articles using Canadian satellite science data; and Active Canadian researchers producing higher level products from Canadian satellite science data
Current Performance:	Considering SCISAT, MOPITT on Terra, and OSIRIS on Odin: Data from these assets are used by hundreds of institutions nationally and internationally in government, industry and academia. ~1000 peer-reviewed scientific journal publications have used data from these assets.
Requirements:	Continuation of the current fleet of Canadian satellite missions; Launching new Canadian and international partner satellite missions; and Ability for Canadian researchers in government, academia and industry to process Canadian satellite science data.
Notes:	Since the launch of SCISAT, MOPITT on Terra, and OSIRIS on Odin, over 500 institutions from more than 50 countries have been involved in publishing research from these assets. About 40 institutions are from Canada, including the Government of Canada through Environment and Climate Change Canada. When these three instruments cease operations (all of them are close or over 20 years since launch), there will be a dearth of Canadian data. Therefore, new instruments are urgently required for this outcome.

Outcome:	**Services are provided to Canadians**
Indicators:	Number of services (i.e. data sets) offered by government, academia and industry to Canadians that are dependent on CSA information (such as remote sensing data, including satellite imagery and science observations).
Current Performance:	Canadians supply data sets for ozone, aerosol and air quality services. Quality controlled and validated data sets are produced for all the Canadian instruments in space and are made available to Canadian and worldwide researchers
Requirements:	Ability to access and process data from Canadian and international satellites and to publish and promote them to government, academia and industry.
Notes:	Items from CSA missions supporting services to Canadians include: one ozone data set, one aerosol data set, one air quality data set delivered to government departments (ECCC), and one complete SCISAT mission data set version.

Outcome:	**Knowledge of Earth and its space environment is enhanced**
Indicators:	Number of scientific publications, presentations, intellectual properties acknowledging or enabled by CSA’s support.
Current Performance:	Academic and government researchers produce significant publications from data from Canadian assets and also from data from other space assets.
Requirements:	Ability to access and analyze data from Canadian and international satellites and publish and promote the results to government, academia and industry.
Notes:	Data from the three currently operating instruments, MOPITT, OSIRIS and SCISAT, have been used in about 1,000 peer-reviewed papers.

Outcome:	**Training of Highly Qualified Personnel (HQP) to be employed in government, academia and industry**
Indicators:	Number of HQP who are trained using Canadian space instruments, satellites, near-space activities, data processes and modelling.
Current Performance:	There is a continuous flow of HQP from Canadian Space Agency projects and missions to positions in academia, government and industry. These HQP form a significant reservoir. There are many people now in entry, middle and senior positions in Canadian High Technology and scientific sectors who were trained in CSA-funded space and near-space projects.
Requirements:	Funding and appropriate projects for training of HQP. Support for early-career HQP to integrate into the field.
Notes:	Considering only the three active Canadian missions, on the order of 500 HQP have been trained over the last three decades.

Outcome:	**Canada’s investment in space benefits the Canadian economy.**
Indicators:	Number of scientific publications, presentations, intellectual properties acknowledging or enabled by CSA’s support
Current Performance:	The Canadian atmospheric community is engaged with government goals. There is significant utilization for carbon cycle, air quality and sustainability.
Requirements:	Ability to access and process data from Canadian and international satellites and publish and promote them to government, academia and industry.
Notes:	There is a robust, internationally recognized space industry and space science community in Canada with strong collaboration between academia, government and industry.

Outcome:	**Industrial Products which benefit the Canadian economy**
Indicators:	Development of Canadian hardware that is of benefit to the economy.
Current Performance:	Canadian researchers working in concert with industrial partners are developing hardware that can be used or marketed in the broader economy. Specific areas are: Fourier transform spectrometers, detectors and mechanisms.
Requirements:	To produce and promote Canadian industrial activities by building state-of-the-art equipment for space and by furthering the development of systems.
Notes:	One example of this area is the development of space Fourier Transform Interferometers/Spectrometers by ABB who are marketing these devices internationally. The development of these devices began in the balloon flights in the 1970s and continues with SCISAT in the 2000s and hopefully beyond.

Outcome:	**Interest in STEM in young people who might become HQP**
Indicators:	Numbers of people showing interest (events, social media, etc.) in Canadian space activities that involve atmospheric science and the environment.
Current Performance:	Many researchers in Canadian space projects work to encourage young people to begin studies on STEM. Some of the young researchers within the current system are the most effective role models.
Requirements:	Funding to release young space scientists to interact with students. Funding to provide work activities appropriate to young people. Support to develop a dedicated STEM outreach program unique to atmospheric and climate science.
Notes:	The human spaceflight program has been very successful with this area, but there has been little opportunity for other space sectors to participate. There is an opportunity to inspire Canada's youth to pursue STEM careers through atmospheric science missions, technologies, resulting datasets, and value added products and services.

Outcome:	**Canadian effective influencing in international space agendas**
Indicators:	Canadian persons in senior positions in international committees/commissions, etc.
Current Performance:	There are not enough Canadian researchers able to free the time to contribute to these international activities. If this were more effective, then Canada would have a higher profile and be able to influence international agendas.
Requirements:	Ability for intermediate and senior Canadian scientists to contribute in international arenas. This means that they need the time and funds to do it.
Notes:	This is a very weak area for Canada.

8. CONCLUSIONS

The climate and the atmosphere are essential for the health and success of Canada and Canadians. Therefore, we need to monitor, model, and understand these critical systems.

- Atmospheric issues impact Canadians' basic needs including food, transport, security, water resources, weather information, and health.

We need Canadian solutions for the uniquely Canadian challenges we face with our large landmass in our cold and changing climate. We must invest across the Space-Based Earth Observation (SBEO) value chain to target the needs and priorities of Canada.

- These activities must be undertaken within Canada to ensure that national needs are met.

The space-based atmospheric science community in Canada is strong and is recognized internationally for our contributions to SBEO research and development across the value chain.

- Over the last 60 years, Canada and Canadians have developed many strengths associated with space-related atmospheric science spanning academia, government and industry.

The atmospheric science community is ready to move forward to develop the next generation of satellite missions to provide the crucial SBEO data needed by Canada.

- Over the past decade and a half, there has been a gap during which no new missions were launched. We have been preparing to fill this gap with new mission concepts.

Canada needs to ensure continued access to space-based atmospheric observations by sustained contribution to the international observing system.

- This requires new Canadian atmospheric science satellite instruments and missions, sustained data processing and validation, improved models, and scientific discoveries.

The atmospheric science community has three new "shovel ready" priority missions that will provide critical SBEO data sets for Canada and the world.

- The measurements made with Canadian instruments and missions will fill gaps in observations and understanding of the Earth's atmosphere and atmospheric processes, over Canada and globally.
- The improved models and data assimilation systems that will result will improve long-term climate projections, as well as near-term predictions of weather, air quality and surface hydrology.

We must leverage Canada's past successes, strengths, and emerging capabilities outlined in this roadmap to address the priorities of the scientific community and Government of Canada with new mission development.

Through these targeted activities and investment, we will build Canadian capacity in key areas and provide critical atmospheric space-based data that will result in applications, services and science for government, academia and industry.

APPENDIX – Canadian-Led Concepts for Instruments/Missions

<u>Mission Concepts that have completed / are completing Phase 0</u>

CASS: The **Chemical and Aerosol Sounding Satellite (CASS)** involves almost 20 researchers from academia, government and industry. Building from the heritage of two successful Canadian missions, **Canada would develop two next generation versions of the OSIRIS (on Odin) and ACE-FTS (onboard Canada's SCISAT)**. The OSIRIS follow-on is the Canadian Atmospheric Tomography System (**CATS**) that has been funded through both the Space Technology Development Program (STDP) and Capability Demonstration programs. The new technologies for the ACE-FTS follow-on, the **CASS-FTS**, have been developed through STDP. CASS would conduct simultaneous measurements with high vertical sampling, covering a wide altitude range from the mid-troposphere to thermosphere, and with a required very high accuracy and stability. CASS would enable the highest vertical-resolution profile measurements of all major greenhouse gases, air quality gases, and ozone-depleting substances. As with SCISAT, the FTS would also measure HFCs from space, the only mission currently proposed with this ability. CASS would enable the advancement of knowledge in the processes driving climate and its changes (greenhouse gases, ozone, ozone-depleting substances, aerosols, focus on Arctic, and HFCs), monitor the Earth's atmosphere as it responds to natural and anthropogenic changes, and probe the coupling between ozone recovery, ozone chemistry, and climate change. Combining these two proven Canadian technologies in a new mid-sized satellite mission, would be feasible for Canada to implement in a 4-5 year time frame.

AIM-North: The **Atmospheric Imaging Mission for Northern Regions (AIM-North)** is an ambitious Canadian mission backed by a science team of over 30 researchers from government, academia and industry. The **dual-satellite system in an innovative highly, elliptical Northern-focused orbit would measure thirteen greenhouse gas and air pollution species**, including ozone, with unprecedented frequency, density, and quality. AIM-North would enable Canada to monitor these trace gases and aerosols near the Earth's surface, with sufficient detail to quantify emissions (or uptake) of greenhouse gases and/or air quality gases from forests, permafrost, wildfires, the oil sands, and cities, with relevant data contributions that impact the health of Canadians and support Canada's international environmental treaty obligations. Each satellite would observe air quality using a dispersive spectrometer and greenhouse gases using an Imaging Fourier Transform Spectrometer (IFTS), an emerging technological advance over an FTS, that enables spectroscopic imaging of the atmosphere. This new adaptation of proven Canadian technology enables unprecedented coverage and has high commercialization potential. An expanded version of this mission with an operational meteorological imager and a small space weather instrument suite is known as the **Arctic Observing Mission** (**AOM**). It revives past Canadian effort for a meteorological imager from the Polar Communications and Weather (PCW) mission and is under consideration via partnership discussions with NOAA, NASA, ESA and EUMETSAT. NOAA has indicated strong interest in AOM, since it is well aligned with their program plans and priorities. AOM would result in geostationary-like weather observations over northern latitudes to address a longstanding observational gap and improve operational weather forecasts for the Arctic and adjacent northern mid-latitudes, while also providing an abundance of data for climate and atmospheric scientific research. Implementing this ambitious mission via an international partnership would be feasible in an 8-9 year timeframe.

A-CCP: A NASA-led mission study is under development to address measurements in **Aerosols, Clouds, Convection, and Precipitation (A-CCP)**. This high priority topic under the 2017 U.S. Decadal Survey on Earth Science and Applications from Space will be implemented by NASA as a designated mission. A proposed contribution by Canada to A-CCP is a world-first combination of **three instruments designed to improve the knowledge and application of the complex processes involved in the interaction between aerosols, clouds, water (in all phases), and radiation**. The three instruments are the:

- **Aerosol Limb Imager** (**ALI**),
- **Spatial Heterodyne Observations for Water** (**SHOW**), and
- **Thin Ice Clouds in the Far-InfraRed** (**TICFIRE**).

This mission science team involves over 20 academic, government, and industry researchers and each of these instruments has undergone several years of technology development, testing and feasibility studies in Canada via academic, government and industry collaboration. Combined, these three passive instruments will monitor aerosol-cloud water interaction in the troposphere and stratosphere to improve polar and global climate change assessment and modeling, enhancing A-CCP science goals to include high and colder atmospheric regions. With daily coverage of both Poles and global upper troposphere-lower stratosphere (UTLS), the measurements will be used to determine the effect of aerosols on atmospheric water cycle, to monitor the formation of cold-dry air anomalies, temperature and humidity, to characterize ubiquitous thin ice clouds, and to spectrally resolve mid and far infrared radiation measurements. This would enable Canada to fill a major gap in Arctic climate research and contribute to improving challenging weather forecasting of the Earth's high latitudes and higher altitudes. NASA has allocated $1.6B (USD) for the A-CCP mission, signifying its high priority status. Key aspects of the mission are still being determined (number of satellites, instrument payloads, orbits). Mission development will begin in 2022, with launches foreseen in 2029 and 2031. If the Canadian instruments proposed are not selected to fly on NASA satellites, they could be proposed to fly on a Canadian or international partnership satellite.

Mission/Instrument Concepts that have been proposed or undergone initial studies

CanACT*,* using the **CATS** instrument, is a proposed microsatellite that would measure stratospheric O_3, NO_2 and aerosol in support of geostationary air quality missions like the NASA TEMPO mission. This mission aims to ensure that air quality measurements from new geostationary satellites provide the maximum benefit to Canada. It would provide improved data sets for monitoring and forecasting of surface pollution and Canada's Air Quality Health Index.

CH_4-SHS is a proposed instrument that would fly on a nanosatellite or as a secondary payload and would use an on-chip-SHS (**Special Heterodyne Spectrometer**) to measure methane total column by glint (~20/day) and mid-stratospheric profiles by solar occultation (~30/day). These measurements would be used to monitor methane emissions on a global scale, to investigate the relationship between total column and upper atmospheric methane and to characterize methane concentrations near coastal wetlands.

Ozone/Dynamics is a proposed mission to measure atmospheric vertical profiles of ozone, winds and temperature in the stratosphere and lower mesosphere (~20-70 km in altitude) using a variety of measuring techniques, to investigate physical and chemical processes responsible for maintaining large-scale atmospheric structures. This mission data would incorporate under-observed wind measurements with atmospheric constituents to enable an improvement of weather, climate, and space weather models vital for climate change analyses.

Infrastructure Components that have been proposed

Validation Capacity: Validation is essential to achieve high quality data from any satellite mission. **Canadian Anchor Sites for Satellite Validation** (**CASSAVA**) is a proposed small network of strategically-located ground instruments across Canada used for atmospheric satellite data validation and long-term scientific analysis. This would enable Canada to validate space-based measurements from existing and new missions in atmospheric and climate science in order to produce and distribute the highest-quality data products globally. Existing Canadian sites are already linked to relevant international ground-based measurement networks, including many other Arctic stations, and contribute to satellite validation of multiple partner satellite missions.

Modelling and Analysis Capacity: Canadian capacity for modelling and assimilation of satellite data is clearly essential to obtaining the most from any space mission investment, but is also important throughout mission development, since it enables studies that can help guide mission design. **Canadian OSSE[3] Data Assimilation facility for Atmospheric Composition satellite missions** (**CODAAC**) is a proposed end-to-end mission science simulation system that serves multiple purposes including mission planning, chemical data assimilation modeling, interpretation of observations, all in order to ensure that future atmospheric composition missions can achieve their scientific objectives and meet the needs of the Government of Canada. This atmospheric composition assimilation facility will provide the modeling tools needed to develop a predictive capability for atmospheric chemistry. It will leverage existing capabilities in the Government of Canada to implement a more comprehensive and coordinated chemical data assimilation science facility that will contribute to developing weather and air quality prediction and warning systems, and contribute to characterize pollutant and greenhouse gas sources, sinks, and trends. This will enable the nation to achieve its objectives in high quality satellite design and development, chemical measurement, instrument operation, and data product development.

[3] Observation Simulation System Experiment