INVESTING IN CANADIAN CLIMATE SCIENCE

AN ASSESSMENT OF THE STATE OF CANADIAN CLIMATE SCIENCE BASED ON A SURVEY OF CLIMATE SCIENTISTS

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Investing in Canadian Climate Science

An assessment of the state of Canadian climate science based on a survey of climate scientists

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By Tristan MacLean.

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ACRONYMS

AMS - American Meteorological Society

CCAR - Climate Change and Atmospheric Research

CFCAS - Canadian Foundation for Climate and Atmospheric Sciences

CO_2 - Carbon dioxide

CREATE - Collaborative Research and Training Experience

ECCC - Environment and Climate Change Canada

FOR - Field of Research

FRQNT - Fonds de Recherche: Nature et Technologies

HC - Health Canada

HFC - Hydrofluorocarbon

HQP - Highly Qualified Personnel

IPCC - Intergovernmental Panel on Climate Change

NCEI - National Centers for Environmental Information

NOAA - National Oceanic and Atmospheric Administration

NSERC - Natural Sciences and Engineering Research Council

PEARL - Polar Environment Atmospheric Research Laboratory

PI - Principal Investigator

TAO - University of Toronto Atmospheric Observatory

WDCC - World Data Center for Climate

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Climate science funding

- Climate scientists expressed a need for long-term, mid-sized grants (approximately CAD$1 million per year) for climate and atmospheric research in Canada.
- 97% of climate scientists think that funding in the field should be increased, with most saying funding should be increased a lot (76%) and some saying a little (21%).
- Climate scientists preferred small to mid-sized grants; 86% would like to see more funding for projects of CAD$1 million or less.

Funding strategies

- When asked whether government funding strategies were sufficient, 82% of respondents expressed concerns about the current funding approach: "We need continuity in climate science-specific funding in order to maintain vital long-term monitoring programs and to attract and retain HQP [highly qualified personnel]."
- The way funding for climate science is disbursed is not suitable for the way climate science is conducted; it does not promote innovation and discovery, and it does not support scientists and staff at different career stages.

Collaborations

- 94% of respondents recommended more funding for government-academic collaborations, but not just for climate science. The need for more collaboration across scientific disciplines is appreciated by a majority of researchers (65%).

Climate science expertise

- Climate scientists report a loss of highly trained individuals as a result of the federal government approach to funding science. 77% of surveyed climate scientists say that highly qualified personnel have left the field.

Resources and infrastructure

- Canadian scientists rely on foreign resources, such as satellites, aircraft and ships. Only 6% of climate scientists surveyed did not rely on foreign resources, while they were extremely or very important for 63% of the scientists.

RECOMMENDATIONS

Supporting climate scientists

» Provide more support for the next generation of climate scientists through clear career paths, small pots of funding to support early career researchers, and funds for support staff.

Planning for the future

» Establish a climate science funding strategy that meets the needs of this diverse, multidisciplinary area of research over the long term.

» Improve funding structures (e.g., timing of announcements, eligibility, size of awards).

» Develop more monitoring stations.

» Include climate science in long-term plans for icebreakers, research aircraft and satellites (existing satellites and the associated expertise are aging, there is a high demand for ship access, and lack of naval resources have impacted Canadian climate science).

Using data to improve climate science

» Develop improved definitions and measures for "climate science" in order to assess funding, monitor progress and evaluate policy.

» Provide climate scientists with better access to climate data, as exemplified by the following comments:

- "Federal government needs to make seamless remote sensing data freely available."
- "Better access to Canadian datasets -- something like a Canadian NCDC [US National Climatic Data Center]."

INTRODUCTION

BACKGROUND

Climate change is one of the defining challenges of our era. The evidence for climate change is overwhelming, and predictions are dire. Both the Canadian government's analysis and international studies have confirmed that Canada faces a dramatic transformation.

The first report from the Canadian national assessment of how and why Canada's climate is changing – Canada in a Changing Climate: Advancing our Knowledge for Action – has concluded that "both past and future warming in Canada is, on average, about double the magnitude of global warming" and that "the rate and magnitude of climate change under high versus low emission scenarios project two very different futures for Canada." The Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C has warned of the urgent need to take action to reduce global net human-caused emissions of carbon dioxide (CO_2) by about 45% from 2010 levels by 2030, reaching "net zero" around 2050 to avoid a 2°C or more rise in temperature.

Canada has international environmental and sustainability commitments, which are addressed through a number of strategies and initiatives. The Paris Agreement commits Canada to enact measures that aim to limit the global temperature rise this century to below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C.[1] In December 2016, Canada's First Ministers adopted the Pan-Canadian Framework on Clean Growth and Climate Change, in order to meet or exceed the Paris Agreement target to reduce greenhouse gas emissions by 30% below 2005 levels by 2030.[2] Canada is also a signatory to the Kigali Amendment to the Montreal Protocol, which commits Canada to an 85% reduction of hydrofluorocarbon (HFC) emissions in Canada by 2036. The Montreal Protocol was designed to reduce ozone depleting substances; HFCs are human-made chemicals that can deplete atmospheric ozone, and they are also powerful greenhouse gases that can be thousands of times more potent than CO_2.

Canada has a unique and distinguished position in terms of global knowledge and understanding of the climate and the Arctic. Canadian climate scientists have pioneered research in atmospheric sciences, meteorology and oceanography. In 1976, the Canadian Meteorological Centre in Montreal launched the first operational global computer weather-modelling system in the world.[3] More recently, in 2009, Canada created the world's first regional-scale underwater ocean observatory connected to the Internet – NEPTUNE – which is capable of monitoring ocean-atmosphere interactions.[4] Given Canada's unique access to the Arctic, its highly skilled scientists and its commitment to climate action, we are in an exceptional position to be a leader in Arctic science, and in climate, atmospheric and ozone research globally.

Canadian climate scientists measure, observe and model many important international environmental indicators and processes, including aerosols; biogeochemical tracers in the Arctic Ocean; sea ice and snow cover; the temperature and other properties of the atmosphere in the high Arctic; and weather predictions and projections of the future climate.[5] The Polar Environment Atmospheric Research Laboratory (PEARL) has been instrumental in monitoring and conducting research on atmospheric ozone, observing the largest ozone depletion event ever seen in the Arctic in 2011, an event that may indicate the potential for climate change to compromise the recovery of the ozone layer.[6] The climate science community in Canada consists of pan-Canadian networks that are geographically widespread and disciplinarily diverse. They also work closely with Canadian government scientists, while contributing to international scientific partnerships; for instance, the Climate Change and Atmospheric Research (CCAR) program has fostered 38 collaborations with US researchers, 31 with European scientists, and four additional collaborations in Brazil and Asian countries.[7] In addition, these projects have trained over 400 highly qualified personnel between 2012 and 2017.

Fundamental climate research plays a crucial role in the models, data and evidence that underpin global decision-making on climate, energy, health and economic policy. Canada has an illustrious history of policy change in relation to the atmosphere, which includes leading the world in addressing ozone depletion through the Montreal Protocol in 1987 and hosting the first-ever international scientific conference on climate change, The Changing Atmosphere: Implications for Global Security Conference in Toronto in 1988.

The Canadian government has historically made significant investments in climate science research, including $118 million awarded to 160 projects between 2002 and 2013, through the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS). Since 2012, a further $35 million has been invested in seven large projects through the Climate Change and Atmospheric Research (CCAR) program.

The CFCAS was established by the federal government in 2000 as an arm's-length foundation with a vision for "the generation and dissemination of knowledge in areas of national importance and policy relevance." The Foundation received CAD$110 million from the government to invest in university-based research in climate and atmospheric sciences. In 2012, the CFCAS directors approached the government for more funding but were rebuffed. That year the government launched the Natural Sciences and Engineering Research Council (NSERC)-administered CCAR initiative; "a five year program designed help [sic] Canadian researchers and scientists understand the economic, environmental, health and safety risks and opportunities of a changing climate and to make sound decisions on adaptation."[8] CFCAS provided over CAD$10 million annually to climate research over 12 years, far more than the CAD$7 million annual funding, on average, from CCAR. Since the CCAR program ended in 2018, Canada has not had a dedicated funding stream for climate science.

The significant costs of infrastructure, such as icebreakers, satellites or Arctic research laboratories, can distort funding trends in the field, giving the appearance of significant investments in fundamental science and scientists. Climate scientists rely heavily on government-funded infrastructure, and yet a flagship Canadian satellite for measuring atmospheric gases and ozone, SCISAT, is now 14 years past its planned lifetime,[9] and carefully planned experiments on the 40-year-old CCGS Amundsen have been cancelled due to a lack of icebreakers.[10]

The 2019 federal budget Investing in the Middle Class proposes up to $21.8 million over five years to support critical repairs and upgrades at the Eureka Weather Station on Ellesmere Island, Nunavut. There is also a critical need for research funding to support climate scientists to make full use of this infrastructure. The PEARL is also located at Eureka; however, the future of PEARL is unclear following the cancellation of the CCAR program and the end of a one-time extension. Canadian climate science requires both investment in infrastructure and in academic research as part of a clear strategy.

Reducing our capacity for climate science research in northern and Arctic regions not only leaves Canada lacking in knowledge about the changing climate, but also fails to place the North at the forefront of government policy and diminishes the involvement of these areas in cutting-edge science. The need for continued science was summed up by a respondent to our survey:

> "There is still a lot to learn about the interactions of climate and the physics, chemistry and biology of Canadian environments (biosphere, atmosphere, ocean). Our climate is changing very rapidly and we have barely characterized the existing system. Our ability to plan for mitigation and adaptation is at risk."

Loss of funding means that international atmospheric data sets and projects that depend on Canadian researchers' work will be negatively affected. It also means the loss of the skills, expertise and productivity of hundreds of climate science trainees, which the country has invested in over the decades.[11]

The Canadian government is funding programs around climate education, mitigation and adaptation through the Pan-Canadian Framework on Clean Growth and Climate Change,[12] and since 2017 they have been developing a new Arctic Policy Framework.[13] However, there is no comprehensive approach to climate change, science and the Arctic, as exemplified by a lack of funding for fundamental scientific research. Fundamental climate research requires long-term support[14] to maintain the infrastructure and expertise required to remain a world leader in this field and to gather the data needed by northern communities and our international collaborations.

This project was undertaken to assess the current state of climate science resources and funding in Canada and offer recommendations to strengthen the field. Our approach was to analyze past and currently available climate funding programs, and consult the climate science community to elicit their needs and opinions. To put this data into context, we also looked at some of the climate science being conducted and the impact of government funding of climate science. We sampled the views of climate scientists through telephone and video interviews, email feedback and an online survey. We combined this information with data from publicly available policy documents, strategies, funding calls, reports, evaluations, peer-reviewed publications, altmetrics and analytics of global competitive-grant data (A detailed explanation of our methodology is provided in the appendix).

The study of the climate, indicators and impacts of climate change, as well as applied science and technological developments to mitigate climate change and the levels of greenhouse gases in the atmosphere, encompasses a vast and diverse range of funding needs. This report is focused specifically on the scientific study of the climate and its interconnected systems, as described by the American Meteorological Society (AMS):[15] "The system, consisting of the atmosphere, hydrosphere, lithosphere, and biosphere, determining the earth's climate as the result of mutual interactions and responses to external influences (forcing). Physical, chemical, and biological processes are involved in the interactions among the components of the climate system." This report will not address important but distinct fields, such as the ecological impact of climate change, the development of renewable energy or the mitigation of fossil fuel emissions.

We conducted interviews with nine academic climate scientists, and our survey received 84 responses from climate scientists working in higher education (82%) and government (12%) as well as non-profit and private sector scientists. Because scientists who have concerns about their research funding are more likely to respond to the survey, we acknowledge that the results may be biased and that the respondents' views may not represent the entire Canadian climate science community.

FINDINGS

> "The current government funding approach is not a well-considered coherent approach but rather an amalgam of funding from diverse departments."

– (survey respondent).

Defining climate science

One of the initial findings from this project was the challenge in defining "climate science" and the way this determines what can be assessed and the analysis possible. There are numerous descriptions and definitions of "climate science," but there isn't a single accepted definition in Canada or worldwide. Without a clear consensus on what constitutes "climate science," attempts to evaluate the effectiveness of policies and funding are severely hampered. For the purposes of this study and for our survey participants we used an AMS definition and the Stanford Encyclopedia of Philosophy description as a guide.[16] In order to carry out analytical investigations of competitive-grant funding of "climate science," we used a combination of Fields of Research (FORs)[17] and search queries, as well as developing a data-based definition from the self-reported areas of expertise of our survey respondents and the Fields of Research[18] attributed to publications arising from the CCAR program. Further details of this methodology are available in the appendix.

Canadian funding

The vast majority of climate scientists (88%) said that federal government grants were extremely or very important for their research. Many of the scientists surveyed also received funding from universities (59%) and provincial governments (51%). A quarter of scientists received funding from industry and 10% from philanthropic foundations. However, for many climate scientists, programs to fund field work, enable collaborations or ensure long-term sustainability are lacking.

We surveyed the climate science community to find out which grant programs they had applied to. The results are displayed in Figure 1.

Figure 1. Funding programs applied to by climate scientists responding to the Canadian Climate Science Funding Survey. Data shown are for programs applied to by at least 10% of the survey respondents.

Program	% of survey respondents
Postdoctoral felllowships (NSERC)	10.7
Postgraduate scholarships - doctoral (NSERC)	11.9
University Undergraduate Student Research Awards (NSERC)	11.9
Major Science Initiatives Fund (CFI)	13.1
John R. Evans Leaders Fund (CFI)	15.5
Northern Science and Technology (Polar Knowledge)	16.7
Advancing Climate Change Science in Canada (NSERC)	17.9
Infrastructure Operating Fund (CFI)	19
Discovery - Northern research supplements (NSERC)	19
Collaborative research and training experience (NSERC)	19
Strategic projects - Group (NSERC)	20.2
Networks of Centres of Excellence (NSERC)	33.3
Research tools and instruments (NSERC)	35.7
Climate Change and Atmospheric Research (CCAR) (NSERC)	38.1
Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)	41.7
Discovery - individual (NSERC)	60.7

In our survey, the program most commonly applied for was NSERC's Discovery Grants (60.7% of respondents). The Discovery Grants program "supports ongoing programs of research with long-term goals" and "provide long-term operating funds."[19] These grants are typically less than CAD$50,000 per year, although some projects have received slightly more. An example is Modelling glacier and ice sheet response to climate change, which started in 2009 and receives CAD$64,000 per year. The Discovery Grants program also has a northern research supplement, which 19% of the survey respondents had applied to. The next two most popular grant programs were CFCAS and CCAR: 34 of the respondents to our survey reported receiving funds from CFCAS, and 32 of those had received funds from CCAR. NSERC's Research Tools and Instruments was also popular (35.7% of respondents); however, as one of our interviewees stressed, despite the progress that has been made developing instruments and equipment, without further funding these resources will be sitting unused for the foreseeable future. With the cancellation of the CFCAS and CCAR programs, there is now no dedicated climate science funding program for Canadian scientists.

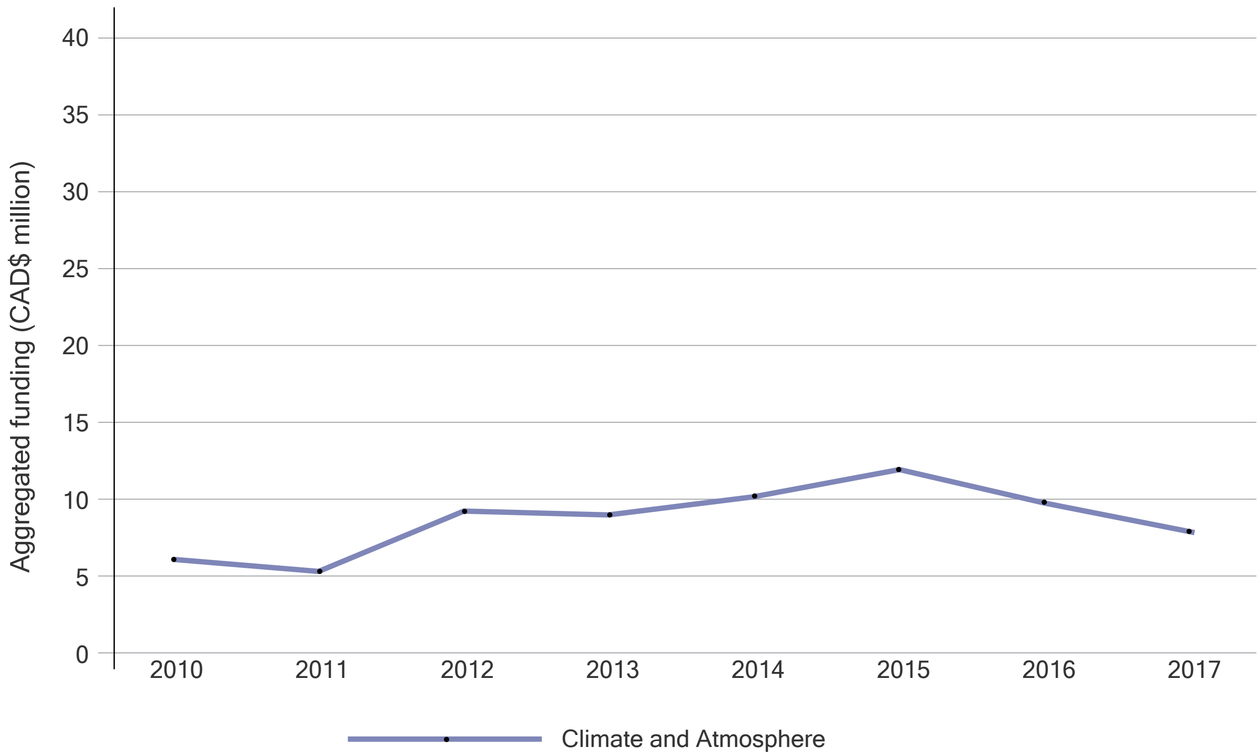
Only 14 respondents had applied to the new Advancing Climate Change Science in Canada award program, which has an anticipated budget of approximately CAD$4.8 million and a focus on cooling technologies, forests and “how to quantify, protect, and enhance natural carbon sinks,” which suggests that it lacks utility for oceanographic, atmospheric or related climate science research. Advancing Climate Change Science in Canada is a collaboration between Environment and Climate Change Canada (ECCC), Health Canada (HC), and NSERC. It requires applicants to collaborate with at least one federal department or agency from the Government of Canada. The program provides funds for projects for up to three years, with a budget up to $180,000 per year.

Similarly, the Polar Knowledge program, Northern Science and Technology was only applied to by 14 of our survey’s respondents. Sixteen (19%) of the survey respondents had applied for the Collaborative Research and Training Experience (CREATE) Program, a program that “facilitate the transition of new researchers from trainees to productive employees in the Canadian workforce.” Less than 10% of respondents had applied for Ship Time, although ship-based research featured commonly in qualitative responses to the survey. A full list of the funding streams included in the survey are detailed in the supplementary materials.

Survey respondents also provided details of funding sources we had not listed as options (these are available in the supplementary materials). These responses identified a few trends, including application to foreign funds (US funders were common) and to government programs that didn’t have a clear climate science focus (e.g., the Natural Resources Canada adaptation platform). Provincial funds in Quebec, Ontario and Nunavut were also mentioned: Fonds de Recherche: Nature et Technologies (FRQNT) in Quebec, Ontario Ministry of the Environment, Conservation and Parks (previously Ministry of the Environment and Climate Change), the Ontario Climate Action program and the Nunavut General Monitoring plan.

Measuring funding disbursed to climate scientists is complicated by the lack of a “climate science” definition that can be used in assessment and tracking. We investigated funding trends for climate science using the NSERC grant database and the Dimensions database. Searching “Areas of Application: Climate and atmosphere” in the NSERC database during the fiscal year 2017-2018 returned 135 awards with a total value of CAD$8.1 million. Between 2010 and 2017, annual NSERC funding of climate and atmosphere research has varied, from a low of CAD$5.5 million in 2011 to a peak of CAD$12.1 million in 2015 (Figure 2).

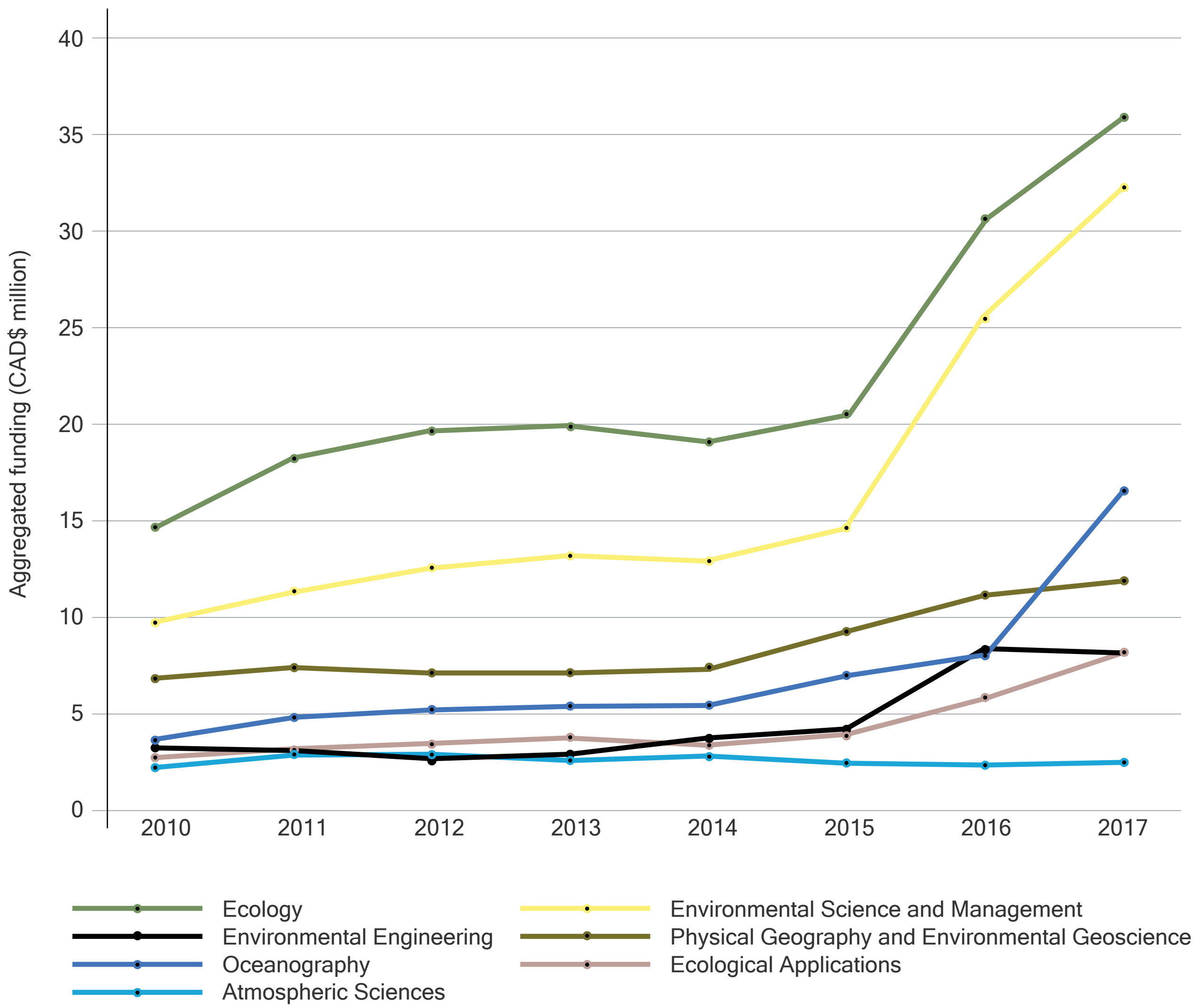
Figure 2. NSERC funding of climate and atmospheric science.



However, on closer examination, we found that this classification included projects that are not climate science (e.g. “ISOSIM - ISOtopes for Science and Medicine” and “Paper-based particulate matter sensors,” a project to develop manufacturing technology of paper-based products for Canadian industry). This classification also did not encompass all of the CCAR-funded projects, with some CCAR projects being classified under other areas, including water and hydrology.

For an additional measure of funding for climate science, we used the Dimensions® database, a global database on grant funds around the world. Major funders in Canada provide their grant data directly to the database, and grants can be classified according to the Australia/New Zealand Standard Research Classification (ANZSRC) system using machine learning trained on extremely large datasets. We looked at the funding of competitive grants for climate-related research across Canada. Within seven key climate-related fields of research, disbursed amounts displayed different trends since 2010, with some fields of research showing significant increases, such as ecology, while others, such as atmospheric sciences, remaining fairly consistent, between CAD$2 and $3 million, since 2010 (Figure 3).

Figure 3. Canadian research grant awards featuring the keyword climate.



Worldwide funding

When we analyzed global funding for climate related research since 2000 (when CFCAS was established), we found that earth sciences receive the most funding (CAD$25.9 billion), with oceanography (CAD$8.5 billion) being the most highly funded discipline within earth sciences. The second-most funding went to biological sciences, with CAD$15.2 billion. We then compared this with climate-related research funding in Canada, where biological sciences (CAD$507.8 million) receive almost twice the funding of earth sciences (CAD$270.5 million). Worldwide, atmospheric sciences receive 8.2% of climate-related research funding, while in Canada they only receive 2.3% of the research funding related to climate. A similar difference in priorities can be seen for oceanography, at 16.1% worldwide versus 6.4% in Canada. Canada also has different climate research priorities than the rest of the world in information and computing sciences, where the worldwide and Canadian allocations are 8.7% and 2.6%, respectively.

A previous study of funding related to climate change found indications of a shift from the fundamental science of the climate to a broader climate change focus. A worldwide analysis of over 27,000 “climate change” projects covering US$14.6 billion of research funding between 2003 and 2016 found changes in funding priorities “from global climate to biological impact and adaptation and, now, towards response and mitigation”.[20] Looking at worldwide competitively funded grant projects containing the keywords “climate change,” the top six research fields in which the work was being classified were: Ecology (8.7%), Environmental Science & Management (8.1%), Physical Geography and Environmental Geoscience (7.5%), Oceanography (5.1%), Geology (4.8%) and Atmospheric Sciences (4.5%). The study found declines in atmospheric, ocean and earth system field research funding between 2003 and 2016. It is worth noting that the Dimensions database does not contain information on non-competitive-grant funding provided to institutes in France and Germany and lacks any data on Chinese investments since 2011. Therefore, this global analysis cannot provide a complete picture of national contributions to climate research.

Funding distribution

One of the frequent statements made in interviews with climate scientists, and in our survey, was a call for more small to mid-sized grant awards.

The majority of climate scientists report receiving between CAD$11,000 and $50,000 per year for their research. It is worth noting the demographics of our survey respondents: 68% were principal investigators (PIs), 9.5% government scientists and 9.5% graduate students. It is PIs who typically apply for grants, and the awards they receive fund the work of a whole group of scientists. Thus, the amount of funding they have is usually greater than that of early career scientists. The number of PIs receiving funding between CAD$101,000 and $500,000 annually has been decreasing since 2013, when 19 of our survey respondents reported receiving this amount, until 2018, when only 13 of our respondents received this amount. In contrast, funding between CAD$51,000 and $101,000 increased over this period, from five to 17 recipients.

Many scientists think that research funding primarily goes to large groups or centres, but others also think that large-scale collaborations are essential. When we asked scientists in our survey for suggestions to improve climate science, an increase in small project funding was, by far, the clearest funding suggestion, with almost half (40) of 84 respondents having the opinion that it should be increased “a lot more”, and a further 31 choosing “more.” In the qualitative responses we received, there was also support for mid-sized grant funding.

> “We need small projects (<$1M) AND large projects (>$1M). We grow our new leaders to begin with small projects and then progress to large projects. At the moment we have no progression between very small and very large.”

The scientists interviewed expressed their strong support for open competitive-grant schemes, that would provide funds for small and larger projects, while also ensuring that a diversity of approaches were funded, and that they span Canadian geographical locations.

There was strong support for climate specific research funding, with 89% of surveyed scientists supporting more funding for a dedicated climate science program.

There was also a lot of support for government-academic collaborations. The CCAR evaluation highlighted their importance, and 94% of respondents to our survey recommended more funding for these types of collaborations.

Aside from the amounts of funding, the way in which federal competitive grants are disbursed was criticized by a number of climate scientists in our survey.

> "A major challenge with climate funding isn't its overall level (if averaged over several years) rather than its reliability. It tends to come in large bursts, which support large initiatives and the development of large groups with specialist expertise – which then have to be disbanded when the funding ends and nothing equivalent is introduced to replace it. This unreliability of funding is a profound obstacle to climate research in Canada."

> "Because there isn't a stable, long-term source of funding for data collection and analysis. Knowledge of Canadian climate requires long-term datasets, as well as measurements across the country. Both are these characteristics are incredibly difficult under current funding mechanisms."

One of our interviewed scientists suggested that time-limited funding programs should support projects with different duration periods so that there would be potential for scientists to move between projects, sharing their skills.

Better communication and scheduling of funding announcements would be a low-cost improvement. In our survey, 48% of climate researchers felt that there is inadequate communication of funding opportunities, and only a quarter of the respondents felt that it was sufficient. One survey respondent pointed out the poor timing of grants in relation to the academic calendar:

> "Provide more advanced notice, more regularity of opportunities, and more practical timing of funding initiatives so that scientists could plan together (I am thinking of the recent advancing climate science call, which notified scientists on 20 November about an LOI [letter of interest] due on 30 November, for a full collaborative proposal deadline due immediately in January, when most university administrative support is closed..)."

Another respondent described it as follows:

> "The timing of the award needs to be better aligned with the academic calendar. Funding should be announced in November or December to allow for recruitment of graduate students, which largely occurs in January. Funding itself should begin in late summer, which would align better with the students beginning in September typically."

There were numerous accounts of poorly managed grant application procedures, with one of the interviewed scientists describing a two-page application that required answers to 26 questions.

A practical low-cost improvement to funding disbursement, mentioned in the survey, was to "allow applicants to specify a preferred year-to-year allocation of their funding in a manner that does not affect the total amount."

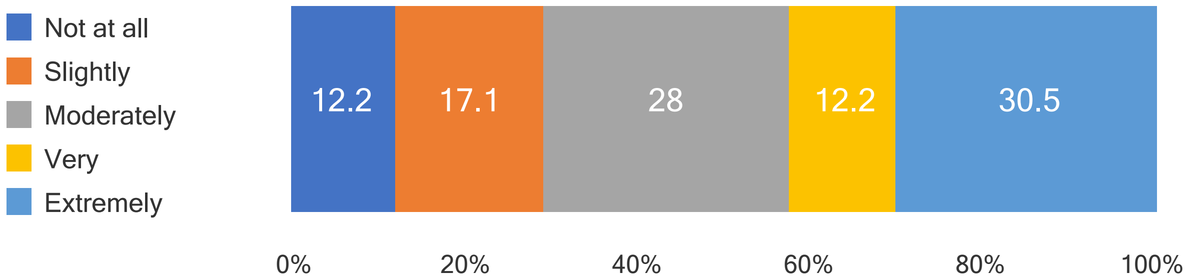
Non-financial support and infrastructure

While government funding is important to climate scientists, so too are other forms of support.

Climate research relies on a multitude of readings and observations; five out of seven CCAR-funded projects required data or samples that cannot be obtained from surface level, such as data from satellites, weather balloons or research aircraft. Remote sensing data from a variety of sources are very important to climate scientists, and 60 of the 82 respondents to our survey use some form of atmospheric- or space-collected data. Many respondents use multiple datasets; for example, one group has taken remote sounding measurements of atmospheric composition at PEARL and at the University of Toronto Atmospheric Observatory (TAO), atmospheric measurements from high-altitude balloons, use ECCC data from radiosondes and ozonesondes, and validate data from various Earth-observing satellite instruments (SCISAT-1, OSIRIS, MOPITT, GOSAT, OCO-2, TROPOMI).[21] Although scientists may not be involved in collecting the data themselves, it is vital to their work. As one survey respondent put it, "I study how atmospheric circulation has changed and will change, and this research depends on the availability and continuity of observational datasets and on the ability to run global climate model simulations, but I do not collect my own observational data."

We surveyed scientists on the importance of various Canadian satellites and instruments to their work and found that roughly half of our survey respondents rely on them to some degree. The importance of satellites varies. We found that the multinational NASA-operated satellite Terra (which carries MOPITT, a Canadian instrument that measures pollution in the troposphere),[22] launched in 1999, had the most users who considered it important to their work (a third considered it moderately, very or extremely important and a further 23% considered it slightly important). Cloudsat is also important to researchers, with 60% of the scientists finding it of some importance. Scientists also regularly rely on foreign satellite data, with 71% of our respondents considering such data at least moderately important to their research (Figure 4).

Figure 4. How important are satellite data from other countries to your research?

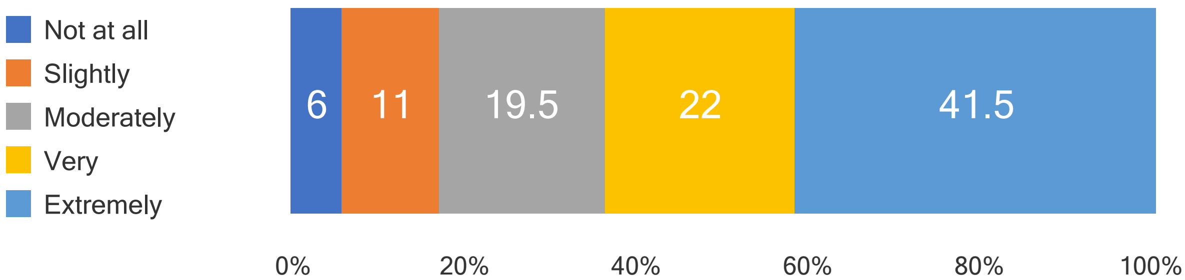


SCISAT and Terra pioneered earth observation and made Canada a leading expert in this area. They have both been very successful, but the expertise that was developed along with them is at risk of being lost if there isn't support for young scientists who can carry forward this accumulated knowledge. Concern was expressed in our study that retirement may lead to the loss of valuable first-hand skills and knowledge in this area.

> "Canada has a strong heritage in two areas of remote sensing – atmospheric measurements and surface sensing. We need at least one new atmospheric mission before the experienced people in academia and industry step back and retire."

A quarter of our respondents rely on ships for their research. Four out of 23 scientists who rely on ships specifically mentioned the CCGS Amundsen, and one mentioned relying on foreign ships: "Yes... but mostly on foreign ships due to the lack of a suitable Canadian vessel" which reflects the difficulties faced by the GEOTRACES project that was diverted to conduct icebreaking.[23] Canadian climate researchers clearly rely on foreign resources to conduct their work. Only 17% of the survey respondents did not state that foreign resources were moderately, very or extremely important (Figure 5). This was reiterated in responses to other questions in our survey.

Figure 5. How important are foreign resources for achieving your scientific goals?



When asked about future funding priorities, the most popular area for increased infrastructure funding was for monitoring stations, with 67 respondents saying they wanted “more” or “a lot more” funding for them. Our survey respondents described the problem:

> “The current weather station network includes much less stations than in the 80s, especially within the boreal forest. It directly impacts our ability to build efficient models to project the impact of climate change in this area.”

> “There will not be enough funding to maintain and repair a large number of weather stations in the next fiscal year, including many population centres.”

International project funding was also a popular choice for more funding; 46 respondents wanted to see “more” and 19 “a lot more” funding for these collaborations.

Access to data is vital to climate science. Canada has been a leader in the use of monitoring data, mathematics and computing in meteorology and climate research. As we enter an era in which we can combine artificial intelligence and “big data” to gain a greater understanding of complex processes, it is essential that Canadian scientists can apply these new tools. As one of our survey respondents stated:

> “The development of high performance computing, artificial intelligence and generally faster computing power could definitely be better leveraged for climate science.”

When asked about future funding strategies, 96% of scientists in our survey said funding for computing resources needed to be maintained or increased. But in order to make the most of computing power, scientists also need better access to climate data. There are a number of large climate data repositories around the world, such as those maintained by the US National Oceanic and Atmospheric Administration (NOAA) (e.g., the National Centers for Environmental Information [NCEI]) and the German-hosted World Data Center for Climate (WDCC).

Canadian scientists need frictionless access to open data. Having invested in the infrastructure to collect the data, it seems to make sense that Canada would collate the data, then safely store it and make it available to the Canadian climate science community. Many Canadian Earth observing instruments are housed on foreign satellites. A Canadian archive would protect against the potential loss or restricted access to data that political changes in other countries could lead to. Scientists suggested better access and support for users, that could be modelled on other services:

> “Federal government needs to make seamless remote sensing data freely available.”

> “Better access to Canadian datasets - something like a Canadian NCDC [US National Climatic Data Center]”

> “Yes. Community facility for climate and weather modelling, data management, including a sustained user support (similar to what NCAR offers)”

ECCC's datasets are now available through the Canadian Centre for Climate Services,[24] but this resource doesn't serve the needs of climate scientists who require datasets from many varied sources, currently housed in different locations and formats, in order to carry out multidisciplinary research.

IMPACT OF CLIMATE SCIENCE FUNDING

Training highly qualified personnel (HQP)

Alongside scientific discoveries and a knowledge base for making policy decisions, climate science is a training ground for numerous students and young scientists. These highly qualified personnel (HQP) require a significant investment over a long period of time and are a valuable Canadian resource. The NSERC CCAR evaluation outlined the value of these HQP:

> "Having access to a larger HQP research contingent allowed networks to collect and analyze larger amounts of data, to conduct much more expansive numerical modelling and simulations using historical data and data collected through the network, and to engage in more collaborative efforts with federal government scientists and/or international researchers."

The interim evaluation identified over 400 HQP involved in the CCAR program by 2016. Though CCAR funding did not support all of these HQP, the funding enabled their involvement in a network of climate science research, and the value of this was described in the NSERC evaluation:

> "There is also a strong indication that HQP received significant opportunities that supported their skills, knowledge and professional development and that these opportunities encouraged, supported and/or aligned with future academic and/or employment pursuits."

Not all of the CCAR programs have completed their final reports, but there are likely to be significantly more HQP, possibly up to 700, who have benefited from involvement in the network in the last three years. When asked about future funding approaches, two-thirds of our survey respondents recommended increasing funding for training new scientists.

In our initial interviews with senior climate scientists, many of them expressed concerns about the impact of cuts in climate science funding and the loss of HQP from the field, from science and from Canada. They described scientists working in other research fields in which there is funding, such as monitoring indoor air quality, leaving science to pursue other more stable career paths, or moving to the United States to continue their climate research. When we asked a broader sample of the climate science community in our survey, 77% of our respondents stated that the Canadian climate science community has lost HQP due to lack of science funding. This represents a significant loss of skills and investment, as well as impacting the perceived support for climate science in Canada. One survey respondent described the problem thus: "We need continuity in climate science-specific funding in order to maintain vital long-term monitoring programs and to attract and retain HQP."

When asked whether the funding approach of the Canadian government was suitable for climate science, one respondent answered:

> "No. In Canada, funding of research has ups and downs. We went from lots of funding during CFCAS, then nothing and then the CCAR program, which funded 7 projects. And now nothing. Stability is required to maintain an active and proficient research community. When these programs ended, we lost many graduate, postgraduates and research assistants that were trained for several years. Most had to be rebuilt when a new program came up. And it was not always possible to do so. In the US or Europe, there are many research programs to which someone can apply (e.g., different agencies, federal departments) so if one program stops, not all is lost. In Canada, the opportunities are limited and the CRD [Collaborative Research and Development Grants] program requires partnership with industry which is not very active in atmosphere-related research."

The short-term nature and unpredictability of funding impacts both science and expertise:

> "It is unpredictable and doesn't allow scientists to develop HQP and their research programs."

> "It's piecemeal and, although significant scientific advances have been made using the current approach, it's unsustainable and unsuitable for maintaining a longer-term cohort of expertise and personnel who are able to advance our understanding of the Arctic and climate further."

As well as the loss of post-doctoral researchers and graduate students after projects end, survey respondents also highlighted the need for continued funding for support staff, to maintain facilities, datasets and retain their knowledge and skills.

> "Hard money is needed to support full-time scientists and technicians. There are no options now between being a grad student or post-doc and a PI, and that is where we lose good people. Post-docs and grad students are too transient to effectively retain and pass knowledge in groups. This is highly inefficient for project continuity. Funding for support staff is critical. You need an ongoing consistent base of people. Grad students and post-docs will come and go (as they should). Funding for infrastructure operations and maintenance is very much needed."

Training HQP is one of the key achievements of Canadian research funding. The number of those trained through government funding programs is often highlighted when measuring impact; however, losing HQP because of science underfunding represents a significant loss of investment, is inefficient and undoes the hard work carried out by the Canadian climate science community.

> "Well established research teams should be able to have a stable support staff. Many programs (e.g., CFI [Canada Foundation for Innovation]) give money to acquire instruments, but it is extremely difficult to obtain funding for the technical support we need."

Publications

Investment in climate science provides many outputs and measures of impact that can indicate the value and effectiveness of this investment. The most traditional measure of scientific output is peer-reviewed publications. The CCAR program has, so far, produced over 500 publications (the digital object identifiers for each publication are listed in the supplementary materials).

The reach and value of these publications can be assessed through proxy measures such as their citations in other peer-reviewed publications or "altmetric" measures including uptake by news outlets, sharing on social media and citations in policy documents. CCAR publications were featured in over 300 news stories, primarily in the US, UK, Canada and Germany. They also received over 3,500 shares on Twitter. CCAR-funded research has also contributed to 15 policy documents in Canada, the UK, the US, Australia, Italy and Switzerland (details are provided in the supplementary materials).

STRATEGIC FUTURE FUNDING

Strategically supporting climate science funding in Canada involves taking approaches and investing in resources that researchers want and need. Some of our survey respondents provided very specific suggestions for future grant funding approaches:

> "A balance of grants in the $100-500K [thousand] range for three years, with opportunities to scale up to larger programs in the $1M [million] range."

> "Medium scale projects with 4-8 PIs would be more efficient and lead to better results. "Big" projects with 30 people all getting $100k [thousand] helps some types of science (more simulations), but doesn't help field research."

> "There needs to be a broad range of grant sizes, everything from a prof and a student camping to medium-sized enterprises like CANDAC/PEARL to large NCE [Networks of Centres of Excellence]-type collaborations."

> "There needs to be funding available for projects of varying sizes (e.g., $10k [thousand] vs. $2 million) and variety of timescales, e.g., 2-year research project and also 5 or 10 years for long-term data collection."

There were also suggestions for infrastructure.

> "An infrastructure operating fund that has annual calls for proposals to fund the operation and maintenance of facilities conducting research related to climate, weather, and air quality. A model for this would be NSERC's former Major Resource Support program or their RTI - Operations and Maintenance program. Annual budget would be on the order of $10M [million]/year, comprising $0.5-1M [million]/year x 15 projects, at 3 years each with 5 new projects selected annually."

Having collated the suggestions of climate scientists in this study, we did a very brief scoping of the costs and timescales of putting them into effect to provide some context for future planning and budgeting.

Table 1. Cost and duration scoping estimates for future funding approaches in climate science

Suggestion	Cost	Duration
Open data (based on 10% of the Digital Research Infrastructure [DRI] contribution program disbursement)[25]	Low (CAD$7.2 million per year)	Ongoing
Small grants (based on CAD$200,000 distributed to 40 researchers)	Low (CAD$8 million per year)	>3 years
Medium-sized climate science grants with partnership requirements (based on Alliance Grants)[26]	Medium (CAD$15 million per year)	1-5 years
Long-term funding (based on CFCAS)	High (CAD$100 million)	>10 years
Monitoring stations (based on the Arctic Environmental Strategy)[27]	High (CAD$100 million)	Ongoing
Aircraft (based on Polar5, a German retrofitted DC-3)[28]	Low (approximately €8.1 million)	Operation lifetime -- up to 50 years
Atmospheric-monitoring satellite (based on SCISAT)[29]	High (approximately CAD$100 million)	Procurement and construction -- 4 years. Operation lifetime -- 5 to 10 years
Polar Icebreaker (based on CCGS John G. Diefenbaker)[30]	Very high (estimates CAD$720 million to CAD$1.4 billion)	Procurement and construction -- 15 years. Operational lifetime -- approximately 25 years

A number of infrastructure and funding programs are underway, such as the RADARSAT Constellation mission and the construction of an Offshore Oceanographic Science Vessel,[31] while funding announcements have also been made during the course of this study, such as funding for repairs to the Eureka Weather Station and plans to build more Arctic vessels and Mid-Shore Multi-Mission Ships to carry out scientific activities.[32] Despite these investments, there is still a lack of funds in crucial and specific areas, such as monitoring and research stations, atmospheric-monitoring satellites and climate science grant programs.

CONCLUSIONS

Since the CCAR program funding ended, Canadian climate scientists have not had access to a mid-sized source of funding. This has resulted in research programs being wound up and has created a crisis for the research at the PEARL. The loss of this carefully structured grant program has also resulted in the ending of some academic-government collaborations and the loss of HQP. Funding for Canadian climate scientists is unevenly distributed. Most climate scientists use the modest Discovery Grants to fund their research, yet almost half of all funding has been concentrated in large awards to a few PIs through the Canadian First Research Excellence Fund and Canada Excellence Research Chairs. Fieldwork in the climate sciences, especially in the Arctic and at sea, can be very expensive. The small amounts of money available through Discovery Grants are not sufficient for work in these regions. Climate scientists are of the opinion that improvements could be made in the way the federal government distributes funding. 86% would like to see more funding for projects under CAD$1 million. They would also like to see a sustained commitment to this research, to enable long-term monitoring and to retain the skills and knowledge of the Canadian climate science community.

> "The largest problem is the intermittent nature of the funding rather than the funding level itself per se. Much of the climate science is being funded on single announcement programs. The timelines to apply for these programs is often very tight, and they are not subsequently renewed. This creates a bad boom and bust cycle, and prevents long-term planning."

Recommendations from the climate science community for future funding approaches focused primarily on providing appropriate funding to support projects that provide stable long-term research in the field, allowing the retention of early career researchers and support staff, while providing them pathways to continue their careers in climate science. As one of our survey respondents put it, "How do we bridge before starting young scientists after PhD and continuing to a career? It seems that after PhD (perhaps a post-doc) there is a chasm beyond to get into new careers."

Senior scientists told us that sharing expertise and ingenuity between government scientists and young researchers could really benefit fieldwork, combining highly valuable experience and knowledge with new perspectives to invigorate research. The benefits of academic-government collaboration are exemplified by the fact that 94% of climate scientists would like to see more funding for academic-government collaborations.

Monitoring stations are vital for climate data collection, and 82% of surveyed climate scientists would like to see more funding for them. We also found that foreign resources, such as ships and satellites, are important to Canadian scientists: 94% of climate researchers use foreign resources, and they are very or extremely important to 63% of them. For this reason, it is important that climate science is taken into consideration when making long-term plans for investments in the Canadian Coast Guard, research aircraft, satellites, and research and monitoring stations, to ensure Canada maintains its position as a global leader in climate research.

Canada's unique and special status in climate and Arctic research has produced a lot of useful data. In our survey, there were calls for better access to this information, with suggestions that Canada should establish a well-supported central repository of easy-to-access open-climate data that would serve the needs of researchers.

There is also evidence that climate science funding has shifted priority to fields monitoring the effects of climate change on the environment and mitigating the impact, such as ecology and environmental science and management. There is no accepted definition of "climate science" that can be used to assess and track statistics in this research area, hampering the ability of researchers, statisticians and the government to identify problems or determine the effectiveness of policies and investments in climate science. A suggestion we received in our survey was for "re-sorting the NSERC categories so that there's a place for interdisciplinary climate science (right now, it goes under disciplinary categories judged by disciplinary panels)." To assess the effectiveness of our climate action, we need better definitions and classifications of climate science.

APPENDIX — Methodological approaches

The information collected in this report was obtained from email responses, video and telephone interviews conducted with climate researchers, an online survey of Canadian climate scientists combined with publicly available policy documents, strategies, funding calls, reports, evaluations, peer-reviewed publications and grant data. Interviews were conducted with PIs and investigators involved in the CCAR program.

Overview of approaches

1. Review of Canadian climate science funding
   a. Identification of funding streams e.g. focus
   b. Funding stream assessment e.g. eligibility, duration, amount
2. Funding data - Grant analytics
3. Analysis of the Impact of Canadian climate science
   a. NSERC CCAR evaluation
   b. CCAR reports
   c. CCAR publication analytics
4. Interviews with CCAR funded climate scientists
5. Survey of Canadian climate science community

Identification of Funding streams

Scientific research is funded from a wide variety of sources and it is beyond the means of this project to identify all the sources of funds that are, or can be, used by scientists who carry out research on the climate. In order to investigate the funding landscape for Canadian researchers we have focused primarily on federal grants and funding, using reports and databases of awards maintained by government agencies. First of all, sources of funds with research focus that could support climate science had to be located. Initially funding streams were identified from the NSERC database,[33] the CCAR evaluation, Tri-Agency websites and web searches. An analysis of the NSERC award database for all grants between 1991 and 2018 in the "Area of Application: Climate and atmosphere", yielded 2,900 awards. Combined with a list of sources of funding provided in the NSERC CCAR evaluation, web searches for recent or upcoming calls for proposals and information provided during interviews of climate scientists yielded 34 competitive funding programs, from 11 Canadian funders, that could potentially be used, or have been used, to support climate science research. This funding list was then expanded upon using information submitted to the Canadian climate science funding survey and grant data in the Dimensions® database. The focus, eligibility, duration and amount of funding was considered and a list of over 40 streams was collated (available in the supplementary materials). These funding streams were then categorized according to the funder and funding priorities e.g. basic research, mitigation, job creation, community engagement, international commitments, and additional information where available was added, such as award amounts.

Funding data - Grant analytics

In order to assess the state of climate science funding in Canada and abroad we required access to a large amount of grant data that could be analyzed and compared in terms of funding levels. Data on competitive-grant awards was accessed from the Dimensions®[34] database. The Dimensions® database includes data on 4,565,325 grants amounting to over US $1.3 Trillion in grant funds across the world. The database was developed in conjunction with research funders and now receives data directly from over 250, with major funders in Canada, UK and USA providing their grant data to the database. The well established Australia/New Zealand Standard Research Classification (ANZSRC) system was adopted by Dimensions® and Artificial Intelligence using machine learning was used to train algorithms to categorize and organize publications and grant awards using large datasets. This Artificial Intelligence approach enables a far more accurate classification of grants, publications and patents than proxies such as journal title. The database contains details of the awards' research, funders, funding amounts, recipient researchers and organizations, associated publications, patents and policy documents. This data can generate the numbers of awards and aggregated funding amounts, which can then be used to generate funding timelines, make comparisons between the country of funders, between provinces, funding agencies and Fields Of Research (FOR). New analytics tools allow us to not only build a better picture of the outputs of research beyond publications and citations but they can now help us to analyze the financial inputs that science receives in the form of competitive grants. While these databases cannot illuminate the many investments in infrastructure, block funding or government science and research, they can act as an indicator of funding trends and priorities, which in turn reflect policy decisions. Further details of the Dimensions® database are available in their 2018 white paper.[35]

Impact of dedicated Canadian climate science

It is not possible to make a comprehensive measurement of the impact of scientific research. However, we wanted to be able to provide some indication of the wider benefits of climate science, beyond the fundamental discoveries. To gain some measure of the impact of dedicated climate science funding we collected information from the NSERC CCAR evaluation, CCAR reports, publication analytics and survey responses.

Interviews

As a result of our advocacy for continued funding for PEARL, Evidence for Democracy had already been in contact with numerous climate scientists, hearing their views and opinions on the state of funding for climate science. In order to gather more robust data than anecdotal accounts can provide we decided to undertake more systematic research on this situation. This started with a series of nine interviews guided by a series of questions encompassing the information that would be ideally collated for the report. To enable agile and responsive interviewing, it was decided that conducting unstructured interviews using these questions as a framework and reminder of the topics to be addressed would lead to better responses. These questions and the resulting answers were then used to inform the design of our survey.

Survey

The survey was designed in conjunction with climate scientists. The survey underwent a number of iterations, internally and externally, with feedback from Evidence for Democracy team members, board members and climate scientists. The survey questions can be found in the supplementary materials.

Our survey gathered data on the following areas:

a) the resources serving the Canadian climate science community

b) the current and future funding needs of the Canadian climate science research community

c) the impact of government funding for climate science

d) opinions on Canadian government climate science strategies and policies

e) the contribution of climate science to evidence-based decision-making

Defining climate science

In this report we have taken a number of different approaches to define “climate science”.

1. Existing definitions e.g. American Meteorological Society.
2. A crowd-sourced definition based on Fields Of Research (FOR) carried out by climate scientists.
3. An analytical definition based on keywords and the Fields Of Research frequency among 551 publications arising from the CCAR grant program.

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