CNC/IUGG: 2019 Quadrennial Report

Geodesy and Geophysics in Canada 2015-2019

Quadrennial Report
of the
Canadian National Committee
for the
International Union of Geodesy and Geophysics

Prepared on the Occasion
of the
27th General Assembly of the IUGG
Montreal, Canada
July 2019

INTRODUCTION

This report summarizes the research carried out in Canada in the fields of geodesy and geophysics during the quadrennial 2015-2019. It was prepared under the direction of the Canadian National Committee for the International Union of Geodesy and Geophysics (CNC/IUGG). The CNC/IUGG is administered by the Canadian Geophysical Union, in consultation with the Canadian Meteorological and Oceanographic Society and other Canadian scientific organizations, including the Canadian Association of Physicists, the Geological Association of Canada, and the Canadian Institute of Geomatics. The IUGG adhering organization for Canada is the National Research Council of Canada.
Among other duties, the CNC/IUGG is responsible for:

- collecting and reconciling the many views of the constituent Canadian scientific community on relevant issues
- identifying, representing, and promoting the capabilities and distinctive competence of the community on the international stage
- enhancing the depth and breadth of the participation of the community in the activities and events of the IUGG and related organizations
- establishing the mechanisms for communicating to the community the views of the IUGG and information about the activities of the IUGG.

The aim of this report is to communicate to both the Canadian and international scientific communities the research areas and research progress that has been achieved in geodesy and geophysics over the last four years.
The main body of this report is divided into eight sections: one for each of the eight major scientific disciplines as represented by the eight sister societies of the IUGG. Each section is titled with the name of the corresponding society and was complied by, and under the direction of, a member of the CNC/IUGG affiliated with that society.
In the interest of compiling and disseminating this report in a timely fashion, no attempt has been made to harmonize the styles of the different sections.
The full text of the report is only available electronically. It is available through the web site of the CNC/IUGG at: http://www.cgu-ugc.ca/cnc_iugg/

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REPORTS of the ASSOCIATIONS

Section 1 International Association of Geodesy (IAG)

Activities in Canada: 2014 – 2018

This report was compiled by Georgia Fotopoulos, Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, Ontario, Canada as the Canadian national correspondent for the IAG.

The following institutions have provided input for this report:

- Natural Resources Canada, Canadian Geodetic Survey
- University of Calgary, Department of Geomatics Engineering
- York University, Department of Earth and Space Science and Engineering
- Ryerson University, Department of Civil Engineering
- Queen's University, Department of Geological Sciences and Geological Engineering
- University of Laval, Department of Geomatics Sciences
- University of New Brunswick, Department of Geodesy and Geomatics Engineering

1. List of Researchers and Research Interests

Natural Resources Canada, Canadian Geodetic Survey

Employee Name		**Status as of 2018-12-01**	**Research Interests**
Dr. Simon	BANVILLE		GNSS, Precise Point Positioning
Mario	BERUBE	(Retired)	GNSS, VLBI
Dr. Jason	BOND		GNSS, RTK Networks, Applications of Geodesy
Marc	CAISSY		GNSS, Real-Time Wide Area Augmentation
Paul	COLLINS		GNSS, Real-Time Wide Area Augmentation
Dr. Mike	CRAYMER		Reference Frames, Geodynamics, Applications of Geodynamics
Dr. John	CROWLEY		Gravimetry, Applications in Hydrosphere/Cryosphere
Brian	DONAHUE		GNSS, Reference Frames, Applications of Geodesy
Dr. Reza	GHODDOUSI-FARD		GNSS, Ionosphere
Dr. Ali	GOUDARZI		GNSS, Precise orbit Determination
Dr. Joe	HENTON		GNSS, Geodynamics, Seismic Strain

Pierre	HEROUX	(Retired)	GNSS, Precise Point Positioning
Dr. Jianliang	HUANG		Geoid modelling, Gravimetry
Diane	JOBIN		Gravity, Gravity applications in resource development
Dr. Omid	KAMALI		GNSS, Precise Point Positioning, Precise orbit Determination
Dr. Calvin	KLATT		Geodetic Applications
Dr. Jan	KOUBA	(Retired)	GNSS, Precise Point Positioning
Francois	LAHAYE		GNSS, Precise Point Positioning
Ken	MACLEOD		GNSS Antenna Calibration
Yves	MIREAULT		GNSS Precise Orbit and Clock determination
Goran	PAVLIC		Gravity, Applications of Gravity
Dr. Bill	PETRACHENKO	(Retired)	VLBI
Dr. Mike	PIRASZEWSKI		Reference Frames, Geodynamics
Dr. Catherine	ROBIN		Reference Frames, Geodynamics
Toni	SEARLE	(Retired)	GNSS, Precise Point Positioning, VLBI
Jason	SILLIKER		Gravity, Applications of Gravity
Pierre	TETREAULT		GNSS
Marc	VERONNEAU		Geoid, Gravity, Applications of Gravity
Dr. Yanlai	ZHAO		Reference Frames, Geodynamics

University of Calgary, Department of Geomatics Engineering

Name	Research Interests
Prof. Michael G. Sideris	Gravity field approximation, industrial surveys, geoid determination
Dr. Elena Rangelova	Geodesy, surveying engineering

York University, Department of Earth and Space Science and Engineering

Name	Research Interests
Prof. Spiros Pagiatakis	Earth system dynamics, gravity field determination, Earth's atmosphere using GNSS/LEO
Prof. Sunil Bisnath	GNSS, positioning and navigation, PPP, geodesy

Ryerson University, Department of Civil Engineering

Name	Research Interests
Prof. Ahmed El-Rabbany	GNSS, multi-sensor integration, mobile mapping

Queen's University, Department of Geological Sciences and Geological Engineering

Name	Research Interests
Prof. Alexander Braun	Geophysics, space geodesy, digital elevation modelling

Prof. Georgia Fotopoulos	Physical and satellite geodesy, positioning/navigation, height systems, surveying

University of Laval, Department of Geomatics Sciences

Name	**Research Interests**
Prof. Emeritus Rock Santerre	High precision GNSS, marine geodesy (hydrography)
Dr. Marc Cocard	Space geodesy, GNSS
Stephanie Bourgon	GNSS

University of New Brunswick, Department of Geodesy and Geomatics Engineering

Name	**Research Interests**
Prof. Marcelo Santos	Physical geodesy, GNSS positioning, navigation
Prof. Richard B. Langley	Physical geodesy, precision GNSS, atmospheric remote sensing using GNSS
Prof. Peter Dare	Precision GNSS, geodetic networks
Dr. Robert Kingdon	Gravity field, geoid modeling, height systems
Prof. Emeritus Petr Vanicek	Gravity field, geoid modeling, height systems

2. List of Publications

The following list of publications is organized by year starting with the latest in 2018 to 2014. Criteria for listing the included publications includes authorship/co-authorship by at least one of the researchers identified in section 1 of this report.

2018

Montanari, A. and M.G. Sideris. 2018. Satellite Remote Sensing of Hydrological Change. In *Global Change and Future Earth: The Geoscience Perspective*, T. Beer, J. Li, K. Alverson (Eds), pp. 57-71. Cambridge University Press.

Piretzidis, D., Sra, G., Karantaidis, G., Sideris, M.G. and H. Kabirzadeh. 2018. Identifying presence of correlated errors and selective filtering of GRACE harmonic coefficients using machine learning algorithms. *Geophysical Journal International* Vol. 215, Issue 1, 1 October 2018, pp. 375-388, https://doi.org/10.1093/gji/ggy272.

Piretzidis, D. and M.G. Sideris. 2018. SHADE: A MATLAB toolbox and graphical user interface for the empirical de-correlation of GRACE monthly solutions. *Computers and Geosciences* Vol. 119, October 2018, pp. 137-150, https://doi.org/10.1016/j.cageo.2018.06.012.

Boggs, K.J.E., Audet, P., Eaton, D.W., Fayek, M., Freymueller, J.T., Hyndman, T., James, T.S., Kushner, P.J., Myers, P., Sideris, M.G., Sullivan, P. and M. Ulmi. 2018. How can EON-ROSE integrate climate science and Earth science? In On-Line *Bulletin of the Canadian Meteorological and Oceanographic Society*, http://bulletin.cmos.ca/eon-rose/, July 7.

Boggs, K.J.E., Aster, R., Audet, P., Brunet, G., Clowes, R., de Groot-Hedlin, C., Eaton, D., Elliott, J., Freymueller, J.T., Hedlin, M., Hyndman, R., James, T., Kushner, P., Morell, K., Rowe, C., Schutt, D., Sideris, M.G., Ulmi, M., Vernon, F. and N. West. 2018. EON-ROSE and the Canadian Cordillera Array - Building Bridges to Span Earth System Science in Canada. *Geoscience Canada* Vol. 45, pp. 97-109.

Ghaderpoor, E., Ince, E.S., S.D. Pagiatakis, (2018). Least-squares cross-wavelet analysis and its applications in geophysical time series. *Journal of Geodesy* (Accepted for publication).
M. El-Diasty, S. Al-Harbi, S.D. Pagiatakis (2018). Hybrid Harmonic Analysis and Wavelet Network Model for Sea Water Level Prediction. *Journal of Applied Ocean Research*, 70, 14-21

Foroughi, I., Safari, A., Novak, P., Santos, M.,2018. Application of radial basis functions in height datum unification. *Geosciences* 8(10), 369.

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Vana S, J Aggrey, S Bisnath, R Leandro, L Urquhart, P Gonzalez (2018). Analysis of GNSS correction data standards for the automotive market. *Proceedings of ION GNSS+ 2018*, 24-28 September, Miami, Florida, pp. 4197-4214.

Bisnath, S., J. Aggrey, G. Seepersad, M. Gill (2018). "Where are we now, and where are we going?" *GPS World*, Vol. 20, No. 4, pp. 42-49.

Niell, J. Barrett, A. Burns, R. Cappallo, B. Corey, M. Derome, C. Eckert, P. Elosegui, R. McWhirter, M. Poirier, G. Rajagopalan, A. Rogers, C. Ruszczyk, J. SooHoo, M. Titus, A. Whitney, D. Behrend, S. Bolotin, J. Gipson, D. Gordon, E. Himwich, and B. Petrachenko. Demonstration of a Broadband Very Long Baseline Interferometer System: A New Instrument for High-Precision Space Geodesy, Radio Science Vol 53, Issue 10, October 2018.

Banville, S; Collins, P; Lahaye, F Model comparison for GLONASS RTK with low-cost receivers; GPS Solutions 22, 52, 2018, https://doi.org/10.1007/s10291-018-0712-3 (NRCan Cont.# 20170171)

Laurichesse, D; Banville, S Instantaneous centimeter-level multi-frequency precise point positioning ; GPS World vol. 29, issue 7, 2018 p. 42-47 (NRCan Cont.# 20180102)

Huang J., Véronneau M., 2018, The spectral response of Stokes's integral to modification and truncation, Erschienen bei KIT Scientific Publishing Schriftenreihe des Studiengangs Geodäsie und Geoinformatik, doi:10.5445/KSP/1000080220
Glenn A. Milne G.A., Latychev K., Schaeffer A., Crowley J.W., Lecavalier B.S., Alexandre Audette A., 2018. The influence of lateral Earth structure on glacial isostatic adjustment in Greenland, Geophys. J. Int., 214, 1252–1266, doi: 10.1093/gji/ggy189

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Smadi, Y, R. Santerre et S. Bourgon (2018). Pont de Québec – Les mouvements de la travée centrale mesurés par GNSS. *The General Science Journal*, août 2018, 9 p. *En arabe*, traduction de l'article paru dans Géomatique (2017), 44(2), pp. 18-22.

Santerre, R., A. Geiger, and S. Banville (2017). Geometry of GPS Dilution of Precision: Revisited. *GPS Solutions*, Springer Verlag, 21(4), pp. 1747-1763.

Santerre, R., and A. Geiger (2018). Geometry of GPS relative positioning. *GPS Solutions*, Springer Verlag, 22:50, 14 p.

Kamali, O., M. Cocard and R. Santerre (2018). A sequential network approach for estimating GPS satellite phase biases at the PPP-AR producer side. *GPS Solutions*, Springer Verlag, 22:59, 11 p.

Dong, Z., C. Cai, R. Santerre and C. Kuang (2018). An Enhanced Multi-GNSS Navigation Algorithm by Utilising a Priori Inter-System Biases. *The Journal of Navigation* (UK), The Royal Institute of Navigation, 71(2), pp. 339-351.

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Santos, M. C., and Nikolaidou, T. (2018) "Trends in modelling neutral-atmospheric electromagnetic delays in a 'big data' world." *Geo-spatial information science*, Vol. 21, No. 2, pp. 75–79. https://doi.org/10.1080/10095020.2018.1461780.

Smolyakov, I. and *R.B. Langley* (2018). "Making It Better: Low-cost Single-frequency Positioning in Urban Environments." *GPS World*, Vol. 29, No. 5, May, pp. 42–48.

Goli, M., Foroughi, I., Novak, P. 2018. On estimation of stopping criteria for iterative solutions of gravity downward continuation. *Canadian Journal of Earth Sciences*, 55(4): 397-405.

Albarici, F. L., G. N. Guimarães, I. Foroughi, M. Santos, and J. L. A. Trabanco (2018) "Separação Entre Geoide e Quase-Geoide: Análise das Diferenças Entre as Altitudes Normal-Ortométrica e Ortométrica Rigoroa." Anuário do Instituto de Geociências – UFRJ, Vol. 41-3/2018, p. 71-81. DOI 10.11137/2018_3_71_81.

Tenzer, R., Foroughi, I. 2018. On the applicability of Molodenkij's concept of heights in planetary sciences. *Geosciences* 8 (7) pp 239.

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McCaffrey, A.M., P.T. Jayachandran, *R.B. Langley*, and J.-M. Sleewaegen (2018). "On the Accuracy of the GPS L2 Observable for Ionospheric Monitoring." *GPS Solutions*, Vol. 22, No. 1, Article 23, doi: s10291-017-0688-4.

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Walter C, Braun A, Fotopoulos G (2018) Impact of 3D attitude variations of a UAV magnetometry system on magnetic data quality. *Geophysical Prospecting*, https://doi.org/10.1111/1365-2478.12727

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2017

Abdelazeem, M., R.N. Çelik, A. El-Rabbany (2017). "An Accurate Kriging-Based Regional Ionospheric Model Using Combined GPS/BeiDou Observations." Journal of Applied Geodesy, Vol. 12, No. 1. DOI: https://doi.org/10.1515/jag-2017-0023. (Published Dec. 21, 2017)

Afifi, A., A. El-Rabbany (2017). "Improved Dual Frequency PPP Model Using GPS and BeiDou Observations." *Journal of Geodetic Science*. 2017;7(1):1-8 DOI https://doi.org/10.1515/jogs-2017-0001.

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Morsy, S., A. Shaker, A. El-Rabbany (2017). "Multispectral LiDAR Data for Land Cover Classification of Urban Areas." *Sensors*, 17, 958; doi:10.3390/s17050958. (Published: 26 April 2017)

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Jobin, D.M., Véronneau, M., Miles, W., 2017. Geological Survey of Canada, Open File 8080, 1 sheet, scale 1:750 000 000. doi:10.4095/299560

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Jobin, D.M., Véronneau, M., Miles, W., 2017. Geological Survey of Canada, Open File 8081, 1 sheet, scale 1:750 000 000. doi:10.4095/299561

Gravity Station Location Map / Carte de localisation des stations gravimétriques, Canada
Jobin, D.M., Véronneau, M., Miles, W., 2017.; Geological Survey of Canada, Open File 8077, 1 sheet, scale 1:750 000 000. doi:10.4095/299557

Horizontal gradient of gravity anomalies map, Canada / Carte des anomalies du gradient horizontal du champ de gravité, Canada
Jobin, D.M., Véronneau, M., Miles, W., 2017. Geological Survey of Canada, Open File 8079, 1 sheet, scale 1:750 000 000. doi:10.4095/299559

Isostatic residual gravity anomaly map, Canada / Carte des anomalies isostatiques résiduelles du champ de gravité, Canada
Jobin, D.M., Miles, W., 2017. Geological Survey of Canada, Open File 8076, 1 sheet, scale 1:750 000 000. doi:10.4095/299556

Observed gravity map, Canada / Carte des valeurs observées de la gravité, Canada
Jobin, D.M., Véronneau, M., Miles, W., 2017. Geological Survey of Canada, Open File 8078, 1 sheet, scale 1:750 000 000. doi:10.4095/299558

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Determining coastal mean dynamic topography by geodetic methods
Huang, J., 2017. Geophysical Research Letters, 44, 11,125–11,128. doi:10.1002/2017GL076020

Analysis of the GRAV-D Airborne Gravity Data for Geoid Modelling
Huang J., Holmes S.A., Zhong D., Véronneau M., Wang Y., Crowley J.W., Li X., Forsberg R., 2017. International Association of Geodesy Symposia, Springer, doi:10.1007/1345_2017_23,

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Section 2 International Association of Geomagnetism and Aeronomy (IAGA)

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This report is divided into four thematic sections, with compiler and contributors as noted:
1. Electromagnetism
2. Aeromagnetism and Geomagnetism, including geomagnetic observatories
3. Paleomagnetism and Rock Magnetism
4. Space Physics (A: Atmospheric Studies, B: Space Plasma Research)

1 Electromagnetism

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1.1 Major discoveries or advances in the past four years

A. Metal Earth

Richard S. Smith (Laurentian University)
Graham Hill (Czech Academy of Sciences, formerly Laurentian University)
Eric Roots (Laurentian University)
Philip Wannamaker (University of Utah)
Jim Craven (Geological Survey of Canada)

Metal Earth is a multidisciplinary project to investigate the processes that lead to mineral deposits. The project is focusing on 13 transects across greenstone belts in the Superior province of the Canadian Shield. The intent is to study mineral-deposit-endowed greenstone belts and those that are unendowed, with a hope of characterizing the features of endowed belts so that mineral exploration efforts can be focused on looking for these characteristics. The geological focused studies involve geochemical sampling, geological mapping (lithologies and structure), geochronology, mantle composition. The geophysics involves seismic reflection studies (with 12-second record length after correlation), passive seismic and long offset data for full waveform inversion, magnetotellurics (MT), gravity acquisition, and compilation of existing magnetic data. These geophysical studies are being supported by acquisition of new physical properties measurements and compilation of existing measurements. The MT data comprising 750 stations was collected by Complete MT Solutions. The stations were primarily collected along traverses proximal to the roads used to collect the reflection seismic surveys. The traverses are comprised of broadband MT stations at a spacing of 5 km. The majority of the traverses also have addition distal broadband stations to provide 3-D constraint, as well as sections close to major structural breaks with alternating audio-MT and broadband MT stations at a spacing of 330-500 m.

Preliminary results have been presented at the Fall AGU meeting in 2018 (Roots et al., 2018).

Roots, E., Hill. G., Frieman, B. M., 2018, GP22A-07: Preliminary Results of the Metal Earth Magnetotelluric Survey. AGU Fall 2018 Abstract.
https://agu.confex.com/agu/fm18/meetingapp.cgi/Paper/368279

B. CCarray

A significant number of Canadian geoscientists have been involved in the development of a new national geoscience project called EON-ROSE (Boggs et al. 2018). This is based on aspects of the Lithoprobe and Earthscope projects, with a goal of covering large areas of Canada with a uniform grid of geophysical instruments. Current plans are to develop an innovative array of seismic, magnetotelluric and geodetic instruments, combined with cameras and other sensors. The project is currently seeking funding from government and industry sources, with the initiative planned to start with an array deployed in the Canadian Cordillera (CCArray).

Boggs, K.J., Aster, R.C., Audet, P., Brunet, G., Clowes, R.M., de Groot-Hedlin, C.D., Donovan, E., Eaton, D.W., Elliott, J., Freymueller, J.T., Hedlin, M.A.H, Hyndman, R.D., James, T.S., Kushner, P.J., Morell, K.D., Rowe, C.D., Schutt, D.L., Sideris, M.G., Ulmi, M., Vernon, F.L., West, N., 2018. EON-ROSE and the Canadian Cordillera Array–Building bridges to span Earth System Science in Canada. Geosci. Can., 45, 97-109. https://doi.org/10.12789/geocanj.2018.45.136

C. Exploration '17

Exploration '17, http://www.dmec.ca/Resources/Exploration-Site.aspx a symposium of the Decennial Mineral Exploration Conferences themed The Challenge of Discovery, provided an important forum for the review of advances in the theory, instrumentation and application of electromagnetic induction methods in airborne, ground, and borehole geophysics. The meeting and proceedings volume covered all aspects of exploration but included numerous papers on electromagnetic induction methods. It represents a valuable integration of state-of-the-art information on the application of electromagnetic induction methods in exploration during the preceding 10 years.

D. Lalor symposium

The Lalor Symposium (British Columbia Geophysical Society 2014) brought together a comprehensive description and comparison of multiple electromagnetic induction investigations, and other geophysical and geological studies, of the deep Lalor volcanogenic massive sulphide deposit in the Flin Flon Belt of the Proterozoic Trans Hudson Orogen in central Canada. The presentations in the original and subsequent offerings of the symposium and published works based on the presentations provide an important geologically-focused examination of modern electromagnetic induction methods.

British Columbia Geophysical Society, 2014. Exploration for deep VMS ore bodies: the HudBay Lalor Case Study. British Columbia Geophysical Society, 2014 Fall Symposium.

E. SIMPEG

The UBC Geophysical Inversion Facility developed and released SIMPEG (Cockett et al. 2015), an open source python package for simulation and gradient based parameter estimation in geophysical applications. This platform currently includes options for potential field, electrical and natural and controlled-source electromagnetic inversion and is already being applied quite broadly including internationally. The 2015 paper describing the package, Cockett et al. (2015), already has 36 citations.

Cockett, R., Kang, S., Heagy, L.J., Pidlisecky, A. and Oldenburg, D.W., 2015. SimPEG: An open source framework for simulation and gradient based parameter estimation in geophysical applications. Computers & Geosciences, 85, pp.142-154.

1.2 Current Research Activities

Summaries are provided on the basis of information available at the time the compilation. Please see list of published works below for the details of activities.

2.1 Lithospheric-scale, crustal-scale, and geological-focused studies

2.1.1 Tectonic studies in the Andes

Martyn Unsworth and students (University of Alberta)

The University of Alberta has led a number of projects that have applied magnetotelluric exploration to studies of subduction zone structure and dynamics in the Andes. This has included (1) studies at the actively deforming Laguna del Maule volcanic field in Chile (2) collection of regional transects in the Peruvian Andes to investigate the causes and effects of flat slab subduction in Southern Peru and (c) initiation of a project to understand magmatism and associated hazards in the Colombian Andes.

2.1.2 Tectonic studies in Western Canada: University of Alberta

Martyn Unsworth and students (University of Alberta)

Existing MT profiles in Alberta and British Columbia have been supplemented with new long-period MT stations to produce a grid that now covers a significant part of Alberta and British Columbia. Major crustal and upper mantle conductors imaged in previous 2-D studies are now clearly defined in 3-D.

2.1.3 Tectonic studies in Western Canada: University of Manitoba

Ian Ferguson (University of Manitoba)

Banafsheh Habibian (University of Tehran)

Alan Jones (Complete MT Solutions)

Juanjo Ledo (University of Barcelona)

MT data from the LITHOPROBE corridors in the northern Cordillera have been re-analyzed using modern methods of tensor decomposition and re-inverted using geologically-constrained 2-D inversions and have provided updated tectonic interpretations.

2.2 Mineral, hydrocarbon and ground-water resource studies

2.2.1 Mineral exploration studies: Laurentian University

Richard S Smith (Laurentian University)

Frédéric E. S. Gaucher (formerly Laurentian University, now at Vale, Sudbury)

Reza Mir (Laurentian University)

Samuel Long (formerly Laurentian University, now at Vale, Sudbury)

A study of the electromagnetic response of the Opemiska deposit in Quebec showed a number of interesting aspects (Gaucher and Smith, 2017a; 2017b). Firstly, in some locations, the ground displayed magnetic viscosity, resulting in a slow logarithmic decay of the secondary magnetic field (Gaucher and Smith, 2017a). This phenomenon had been noted in Australia and attributed to "superparamagnetic" maghemite in the weathered cover. However, in this instance, there was no weathered cover, only exposed rock. Measurements with an EM induction spectrometer on a bedrock sample gave a spectral behavior consistent with magnetic viscosity. Further, observations in a scanning electron microscope showed fine grained magnetite, and magnetic viscosity is known to be more prevalent in fine grain samples. In this case the grains looked to be crushed by some type of structural deformation. The transient electromagnetic survey was intended to look for Cu-Au mineralization (Gaucher and Smith, 2017b). In some cases, the ore is highly conductive and strong responses could be identified and modelled; in other cases, there was massive chalcopyrite ore that was not conductive. Possible explanations for the lack of conductivity could be that the ore is a semi-conductor, or that it is surrounded by an insulating mineral.

Another electromagnetic and electrical study at the Canadian Malartic mine in Quebec (Mir et al., 2019) showed an interesting correlation between zones of low resistivity and areas of greater structural complexity. These zones of structural complexity were also correlated with high gold content. Hence electromagnetic or electrical methods could be used as an indirect (proxy) indicator of gold. In this case, it was necessary to look at the data at depths greater than those that are impacted by conductive overburden.

A study of the electrical resistivity data collected at the Midwest deposit in the Athabasca basin of Saskatchewan was undertaken to see if the resistivity data is capable of seeing a subtle conductive alteration zone between a highly conductive graphitic conductor at depth and a conductive lake at surface (Long et al., 2017). The forward modelling shows pseudo sections dominated by the surface features. The inverse sections show a feature at surface and one at depth, with a smooth narrow feature joining the two which could be the alteration or could be an artifact of the smoothing regularization. The study showed that a combination of forward modelling followed by inverse modelling was the best way of determining that the smooth narrow feature was indeed alteration.

Gaucher, Frédéric E. S. and Smith, Richard S., 2017b, Exploring for copper–gold deposits exhibiting a wide range of conductivities with time–domain electromagnetics at Opemiska, Canada. In "Proceedings of Exploration 17: Sixth Decennial International Conference on Mineral Exploration" edited by V. Tschirhart and M.D. Thomas, 2017, 779–787

2.2.2 Mineral exploration studies: Geological Survey of Canada

Vicki Tschirhart, Jim Craven, E. Schetselaar, S.M. Ansari (Geological Survey of Canada)
Jessica Spratt, Magnetotelluric Contractor, Wakefield, Quebec

The Geological Survey of Canada has collected new long-period MT data over the Patterson Lake corridor, northwestern Saskatchewan, to examine deep fluid pathways related to uranium deposit formation, and in conjunction with gravity and magnetic methods, model the regional crustal structure.

A magnetotelluric survey was conducted as part of the Brock Inlier Project, Northwest Territories, in the second phase of Natural Resources Canada's Geo-mapping for Energy and Minerals (GEM) program. Co-located audio- (AMT) and broadband (BBMT) magnetotelluric sites were collected at 17 locations during the 2015 summer field season. The Brock Inlier overlaps the eastern edge of the largest gravity and magnetic anomaly in North America, the Darnley Bay anomaly. It has been suggested that the anomaly is a result of a deeply buried Ni-Cu-PGE magmatic sulphide deposit similar to that of Noril'sk in Russia. Magnetotelluric were acquired along an east-west transect to trace sedimentary rocks layers westward from the Brock Inlier into the subsurface and to improve understanding of the nature, size and depth of the Darnley Bay anomaly.

In smaller scale mineral exploration electromagnetic studies, inversion methodology and algorithms are being developed for inverting magnetotelluric data for complex three-dimensional Earth conductivity models such as for mineral deposits and results have been applied to the Lalor deposit, Manitoba (Ansari et al., 2019).

2.2.3 Mineral exploration studies: University of Alberta
Martyn Unsworth and students (University of Alberta)

The University of Alberta has undertaken investigations of how magnetotellurics and ZTEM data can be combined in exploration for porphyry copper deposits. This has included collection of new datasets to ground truth the airborne data, and development of joint inversion algorithms.

2.2.4 Mineral exploration studies: University of Manitoba
Ian Ferguson and students (University of Manitoba)

The Duport Gold Deposit in Shoal Lake, Northern Ontario was investigated using integrated electromagnetic and magnetic methods and both airborne and ground geophysical data (Ferguson et al., 2016). The airborne data was also used to define bathymetry and sediment thickness in the surrounding area of Shoal Lake (Traa, 2016).

2.2.5 Hydrocarbon-related studies in Central and Northern Canada
Jim Craven (Geological Survey of Canada)
Brian Roberts (Geological Survey of Canada)
Ian Ferguson and students (University of Manitoba)

Several magnetotelluric (MT) surveys have been conducted in northern Canada as part of the Geological Survey of Canada's second phase of the Geo-mapping for Energy and Minerals (GEM-2) program's Hudson-Ungava Project. A 22 site magnetotelluric (MT) survey was conducted in the Kaskattama Highlands, northeastern Manitoba, in summer 2017 as part of the GEM 2 program (Craven et al. 2017). The primary target was the underlying Paleozoic Hudson Bay Basin rocks: the survey crosses an area in which a drill-hole reveals anomalous Paleozoic stratigraphy including a Cretaceous(?) shale unit and the absence of some Silurian units. Underlying Precambrian basement rocks include the Fox River Belt of the Superior Boundary Zone, close to its truncation by the Winisk River Fault. A 26 site MT survey was conducted on Cape Donovan on Southampton Island to image a hydrothermal dolomite occurrence and the Paleozoic rocks present on the cape (Craven et al., 2018, Marks, 2019).

2.2.6 Geothermal studies
Martyn Unsworth and students (University of Alberta)

With funding from the Canada First Research Excellence Fund, the University of Alberta is conducting research into the development of sources of low-carbon energy for the future. Under the auspices of this project, geophysical exploration, including magnetotellurics, is being used to characterize a number of geothermal systems in Alberta and British Columbia.

2.2.7 Groundwater studies: Geological Survey of Canada
Greg Oldenborger and others (Geological Survey of Canada)

Ian Ferguson and students (University of Manitoba)

Airborne time-domain electromagnetic (TEM) data have been inverted and used in combination with supporting geophysical and geological information to develop detailed and complex maps of regional bedrock topography, and to construct 3D geological models of buried valley systems with little surface expression (Sapia et al., 2015a,b; Oldenborger et al., 2016). These models provide insight into formative processes and aquifer geometry and connectivity relevant to groundwater resource management for consumption, agriculture and industry.

2.2.8 Groundwater studies: University of Manitoba

Ground TEM data and magnetic data have been collected over multiple buried valleys in Manitoba to image the base and internal structure of these features (Naseem, 2016, Taniguchi 2019).

2.2.9 Sea-water intrusion mapping

Erwan Gloaguen, Bernard Giroux (Institut national de la recherche scientifique)
Christian Dupuis (Université Laval)

Fresh water resources are decreasing at the Îles-de-la-Madeleine islands (Québec) due to increased demand and the sinking of the islands, a consequence of the continental uplift. The combined action of these two factors cause the raising of the sea water level. A monitoring program combining TEM with hydrogeological measurements is underway to identify critical zones and help management of the resource. A mobile land TEM system is being developed for the project.

2.3 Shallow geological, environmental, and geotechnical surveys using electromagnetics

2.3.1 Interdisciplinary studies

L.R. Bentley (University of Calgary)
R. Lauer (University of Calgary)
M. Hayashi (University of Calgary)
E. Cey (University of Calgary)
C. Ryan (University of Calgary)

Research groups in the Department of Geoscience, University of Calgary have extensively integrated geophysical surveys into multi-disciplinary hydrogeologic and environmental studies. These studies regularly include electromagnetic methods such as EM 31, electrical resistivity tomography (ERT) and ground-penetrating radar (GPR). The overall objectives of the studies is to develop stratigraphic, soil moisture and geochemical models that are consistent with all drill logs, surface observations, geochemical sampling, hydrologic monitoring, modeling results and petrophysical parameter distributions as defined by the geophysical studies. Because the geophysical studies provide continuous spatial distributions of petrophysical parameters, they are often key to tying the variety of point measurements together. Recent projects have included using ERT to map distribution of saline fingers into fresh groundwater along the margins of a hyper saline lake (Bentley et al. 2016); using ERT, EM 38 and direct push electrical conductivity to map the soil moisture distribution of a tailings dyke as part of a hydrogeologic study of fluid movements within the dyke (Booterbaugh et al. 2015) and using geophysical methods including ERT, GPR, seismic refraction and bottom of snow pack temperature measurements in support of a hydrologic/hydrogeologic study of an inactive rock glacier in the Canadian Rocky Mountains (Harrington et al. 2018).

2.3.2 Infrastructure studies
G.A. Oldenborger and others (Geological Survey of Canada)

Electromagnetic induction data along with galvanic and capacitively-coupled electrical resistivity surveys have been used for predictive assessment and classification of permafrost terrain for infrastructure vulnerability (Oldenborger et al., 2015; Oldenborger and LeBlanc, 2015; Oldenborger and LeBlanc, 2018). Apparent conductivity exhibits correlation with patterns of thaw sensitive ground, and time-lapse surveys suggest changes in unfrozen water content within near-surface permafrost.

2.3.3 CO2 storage monitoring: Alberta
Bernard Giroux (Institut national de la recherche scientifique)
Thomas Daley (Lawrence Berkeley National Laboratory)
Cornelia Schmidt-Hattenberger (GFZ Potsdam)
Klaus Spitzer (TU Bergakademie Freiberg)
Don Lawton (University of Calgary)

A pilot project is underway at the Field Research Station (Alberta) to evaluate the performance of various monitoring techniques for detecting CO2 in the intermediate zone (~ 300 m). Downhole magnetoresistivity, downhole TEM, crosswell EM, as well as surface and downhole ERT measurements are part of the geophysical monitoring program. Baseline surveys were carried out in 2017 and 2018. CO2 injection has started in 2018 and should end in 2019, after 100 t has been injected. Repeat surveys are planned for 2019.

2.3.4 CO2 storage monitoring: Aquistore Sequestration Site, Saskatchewan
Jim Craven (Geological Survey of Canada)
Brian Roberts (Geological Survey of Canada)
Ian Ferguson (University of Manitoba)
Joe McLeod (University of Manitoba)
Bernard Giroux (Institut national de la recherche scientifique)

Magnetotelluric (MT) soundings were conducted in a 4×4 km area at the Aquistore CO2 sequestration site at Estevan, Saskatchewan, Canada in 2013, 2014 and 2015, prior to CO2 injection (McLeod et al. 2015, 2018). The pre-injection electromagnetic study also included surface controlled-source measurements using a 1 km long, 30 A electric bipole source. Recordings of the radial electric field component were made in 2013 and 2015 surveys along an inline receiver profile at offsets up to 9.5 km.

2.3.5 Archeological electromagnetic studies
Ian Ferguson (University of Manitoba)
David Landry (University of Manitoba)
Brooke Milne (University of Manitoba)

Surface and near-surface physical properties of a Paleo-Inuit sites located in the interior of southern Baffin Island, Nunavut, Canada have been mapped using multi-method approaches including laser scanning, electromagnetic induction, and ground penetrating radar. The electromagnetic induction approach has been particularly useful for imaging variations in magnetic susceptibility associated with granitic boulders used in tent rings (Landry et al. 2015) and imaging regions of lower susceptibility associated with a chert deposit at a lithic quarry site (Landry et al. 2018).

2.4 Theoretical electromagnetic modelling and inversion studies

2.4.1 Theoretical electromagnetic studies: Laurentian University

Richard S Smith (Laurentian University)
Jacques Desmarais (formerly Laurentian University, now at the University of Saskatchewan)
Michal Kolaj (formerly Laurentian University, now at the Geological Survey of Canada)
Tomas Naprstek (Laurentian University and the National Research Council of Canada)
Yongxing Li (formerly Laurentian University, now at Nova Mining Exploration Solutions)

In active EM methods extensive use of a simple yet versatile "dipping" sphere model has been made by the group at Laurentian. Desmarais and Smith (2016a) mathematically decomposed the response of a buried dipping conductor into component with spatial profiles characteristic of those from horizontal, vertical (perpendicular) and vertical (parallel) to the profile. Using this decomposition, it is possible to estimate the depth, dip, strike and offset of the conductor. A similar study showed that measuring the y component and of using y and x directed transmitters in additional to the traditional z directed transmitter (Desmarais and Smith, 2016b) allowed the geometric parameters to be estimated and the identification of conductors that are only weakly coupled to the z-directed transmitter. The same sphere model was used to investigate the ability of the InfiniTEM system to explore for conductive ore deposits. A model study (Desmarais and Smith, 2015a) showed that when optimal survey parameters were selected (base frequency, sensors, loop spacing, etc), the system could see a target as a depth of about 900 m. Methods for interpreting airborne (Desmarais and Smith, 2015b) and ground electromagnetic (Desmarais and Smith, 2015c) data were developed using this sphere model as well. It was found that the total component was a robust tool for identifying the location, depth and dip of conductors. Finally, the sphere model has been extended to calculate the EM response when the sphere is buried below conductive overburden (Desmarais and Smith, 2016c).

A fast and rapid tool for interpreting active electromagnetic data has been developed by Kolaj and Smith (2017). The tools solves for the strength and orientation of electric or magnetic dipoles in the ground that can explain the measured response. The method was tested with some success on mineral and environmental data.

The radio imaging method (RIM) is a tool commonly used in Sudbury for delineating mineralized zones between two boreholes. The transmitter (operating at approximately 1 MHz) is in one borehole and the receiver is in the other hole are used in a tomographic mode. Simple tools for interpreting this data usually ignore changes in the magnetic permeability or dielectric permittivity. A study by Naprstek and Smith (2016) showed that the effect of dielectric permittivity is important and should be taken into account. More extensive studies developed tools for simulating the RIM response in a conductive and dielectrically permittive environment (Li and Smith, 2015). Using simulated data, it was shown that the straight-ray imaging tool only works well in specific circumstances (Li and Smith, 2018a). Hence, a new interpretation tool was developed that is capable of modelling a broader range of conductive and permittive environments (Li and Smith, 2018b, 2019).

2.4.2 Theoretical electromagnetic studies: Memorial University of Newfoundland

Colin Farquharson, Peter Lelièvre, Seyedmasoud Ansari, Hormoz Jahandari, Jianbo Long, Xushan Lu (Memorial University of Newfoundland)

Farquharson & his research group have focused on the development and implementation of forward-modelling and inversion methods for Earth models parameterized in terms of unstructured tetrahedral meshes. These meshes allow for general, complex models to be built, with topography and geological interfaces being incorporated into a model with as fine a resolution as desired. These meshes also enable regions of interest to be discretized finely with the discretization coarsening substantially towards the extremities of the computational domain, thus allowing for an efficient overall distribution of cells. Farquharson & his group have developed forward-modelling software for frequency- and time-domain controlled-source EM methods (small loop, large loop and grounded-line sources), and forward-modelling and inversion software for MT. During the course of the research for and development of these codes, the group has also developed software for the building, editing and manipulation of Earth models parameterized in terms of tessellated interfaces and unstructured tetrahedral meshes (FacetModeller, PODIUM).

2.4.3 Theoretical electromagnetic studies: University of Saskatchewan

S.L. Butler and students (University of Saskatchewan)

S.L. Butler has carried out some theoretical work related to the electrical resistivity method and in particular has shown a simple analytical formula that is useful for estimating the depth of investigation for any arbitrary 4 electrode array.

Forward models of geophysical electromagnetic techniques have also been developed using the commercial finite element modeling package Comsol Multiphysics. With students Todd LeBlanc and Ang Li, these are being used to invert for resistivity structure in a potash mine and to investigate powerline noise in magnetotellurics.

2.5 Electromagnetic induction instrument advances

2.5.1 Electromagnetic instrument advances: Laurentian University

Richard S Smith (Laurentian University)

Jacques Desmarais (formerly Laurentian University, now at the University of Saskatchewan)

Michal Kolaj (formerly Laurentian University, now at the Geological Survey of Canada)

Joshua Lymburner (formerly at Laurentian University, now at Hudbay Minerals Inc)

A new approach to active source electromagnetics is being taken at Laurentian. The arrays of EM sensors that have been advocated for active source studies has been extended to arrays of transmitters. An empirical study along a single undertaken by Lymburner and Smith (2015) showed that multiple transmitter locations and spatial stacking of these transmitters could substantially improve the signal-to-noise ratio and the depth of exploration. These concepts were extended to an array of transmitters spread over an area rather than a profile (Kolaj and Smith, 2015). Different spatial stacks are able to emphasize conductors in certain locations and orientations and suppress others. As this spatial stacking can be done after the survey, the data can be used to investigate in detail a volume of interest. Tools for interpreting the large volume of data generated have been proposed by Kolaj and Smith (2015). The method can also be extended by using arrays of three-component transmitters to direct the fields at any orientation and any location in the subsurface, ensuring that all conductive bodies will be excited electromagnetically. The use of a three-component transmitter has been proposed for detecting highly conductive deposits such as nickel, which are difficult to see in airborne electromagnetic data (Smith, 2018).

2.6 Physical electrical property studies

2.6.1 Physical electrical property studies: Laurentian University

Richard S Smith (Laurentian University)
Devon Parry (formerly Laurentian University)

In a study of the conductivity of various host and ore mineral in the Sudbury area, Parry et al. (2016) found that a combination of tools was necessary for measuring the conductivity. The hand-held tools were capable of measuring the conductivities of core samples from 0.5 to 10 000 S/m (these samples were primarily mineralized with unmineralized samples being below the sensitivity of the instrument). Downhole inductive tools gave measurements in a range of 0.01 to 3 S/m, and downhole galvanic resistivity tools were most sensitive in the range from 10-5 to 0.01 S/m (primarily unmineralized).

1.3 **Published Research over the past four years**

3.1 Papers in Refereed Journals

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3.2 Other Refereed Material

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3.3 Government Reports

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McLeod, J., Craven, J.A., Ferguson, I.J., and Roberts, B.J., 2015, Overview of the 2013 and 2014 baseline magnetotelluric & controlled source electromagnetic studies of CO2 sequestration at the Aquistore site near Estevan, Saskatchewan, Open File 8101, 44p. doi:10.4095/299100

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3.4 Theses

(Note that in some cases, theses have not been included if the material has been subsequently published.)

Duncan, P., 2016. Hydrogeophysics of sites in the South Tobacco creek and Elm Creek watersheds in southern Manitoba. B.Sc. (Hons.) Thesis, U. Manitoba, Winnipeg, Canada.

Dunham, M., 2016. Application of 3D marine controlled-source electromagnetic finite-element forward modelling to hydrocarbon exploration in the Flemish Pass Basin offshore Newfoundland and Labrador, Canada. M.Sc. Thesis, Memorial University, St. John's, Canada.

Jones, D., 2017. 3D Geophysical electromagnetic forward modeling of complex graphitic fault zones. M.Sc. Thesis, Memorial University, St. John's, Canada.

Kary, B., 2017. Investigating Schwarz domain decomposition based preconditioners for efficient geophysical electromagnetic field simulation. M.Sc. Thesis, Memorial University, St. John's, Canada.

Lee B.M. 2015. Three-Dimensional electromagnetic imaging of porphyry copper deposits with MT and ZTEM Data. MSc thesis, U. Alberta, Edmonton, Canada.

Marks, J., 2019. Delineation of a hydrothermal dolomite occurrence on Cape Donovan, Southampton Island using magnetotellurics. B.Sc. (Hons.) Thesis, U. Manitoba, Winnipeg, Canada.

McLeod, J., 2016. Electromagnetic monitoring of CO2 sequestration at the Aquistore site, Estevan, Saskatchewan, Canada. M.Sc. Thesis, U. Manitoba, Winnipeg, Canada.

Miles, D.M., 2017. Advances in fluxgate magnetometry for space physics. PhD thesis, U. Alberta, Edmonton, Canada

Nalepa, M., 2016. Synthetic modelling study of marine controlled-source electromagnetic data for hydrocarbon exploration. M.Sc. Thesis, Memorial University, St. John's, Canada.

Naseem, C.Q., 2016. Magnetic delineation of the Spiritwood buried valley aquifer, southern Manitoba using airborne and ground data. B.Sc. (Hons.) Thesis, U. Manitoba, Winnipeg, Canada.

Squires, C., 2016. A synthetic modelling study and assessment of marine electromagnetic data using unstructured tetrahedral meshes with applications to hydrocarbon exploration in the Flemish Pass Basin, offshore Newfoundland. M.Sc. Thesis, Memorial University, St. John's, Canada.

Taniguchi, S., 2019. Delineation of the Medora-Waskada buried valley aquifer near Souris Manitoba using time-domain electromagnetics. B.Sc. (Hons.) Thesis, U. Manitoba, Winnipeg, Canada.

Traa, M., 2016. Analysis of helicopter electromagnetic data set in order to map sediment thickness and conductivity in northwestern Shoal Lake, Ontario. B.Sc. (Hons.) Thesis, U. Manitoba, Winnipeg, Canada.

4) PARTICIPATION IN IAGA THEME INTERNATIONAL AND NATIONAL MEETINGS OVER PAST FOUR YEARS
Division VI
Registered Canadian members: 10
Canadian Representative: Martyn Unsworth, University of Alberta
23rd EM Induction Workshop: Chiang Mai, Thailand, 14-20 August, 2016
Attendance by Canadian scientists and students: 6
Program Committee Chair: Ian Ferguson, University of Manitoba
Convener: EM Induction Education and Outreach Session: Ian Ferguson, University of Manitoba
24th EM Induction Workshop: Helsingor, Denmark, 13-20 August, 2018
Attendance by Canadian scientists and students: 8-10

2 Aeromagnetism and Geomagnetism

Contributions from:
Hayward, Nathan (NRCan/RNCan) nathan.hayward@canada.ca
Tschirhart, Victoria (NRCan/RNCan) victoria.tschirhart@canada.ca
Pilkington, Mark (NRCan/RNCan) mark.pilkington@canada.ca
Thomas, Mike (NRCan/RNCan)
McCausland, Phil (University of Western Ontario)

2.1 Awards

Catherine Johnson (Canada) has been awarded the 2019 Shen Kuo Award for Interdisciplinary Achievements of the International Association of Geomagnetism and Aeronomy (IAGA) of IUGG

2.2 Aeromagnetic Surveys

There have been a number of aeromagnetic activites over the past four years, mostly related to the GEM – Geomapping for Energy and Minerals Program of the Geological Survey of Canada. These have included the acquistion of thirteen airborne magnetic surveys since 2015 (see the Geoscience Data Repository http://gdr.agg.nrcan.gc.ca and table 1.1, below) and the creation of aeromagnetic compilations of Yukon-Alaska (GSC Open File 7862) and the Great Bear Magmatic zone (GSC Open File 8035).

Published work over the past four years includes magnetic interpretation in Yukon-Alaska (Hayward, 2015), the tectonics and mineral prospectivity of the Great Bear magmatic zone (Kerswill et al., 2016), 3D structrure of the Rae craton (Snyder et al., 2015) and foreland of the Trans-Hudson orogeny (Percival and Tschirhart, 2017), the Thelon Basin, Nunavut (Tschirhart et al., 2017; Tschirhart and Pehrsson, 2016) and the Montresor metasedimentary belt, Nunavut (Tschirhart et al., 2015). Magnetic data have also been used in an interpretation of salt structures in the Gulf of St. Lawrence (, and used for modelling saucer-shaped sills on Ellef Ringness Island as part of the High Arctic Large Igneous Province Evenchick et al., 2015). Theoretical and practical advances have also been reported for 3D magnetic inversions (Pilkington, 2016), the use of edge detecors in inversions (Pilkington and Tschirhart, 2017), potential field continuation (Pilkington and Boulanger, 2017).

GSC programs conducting research related to aeromagnetics:
Targeted Geoscience Initiative 5 uranium fluid pathways (leads: V. Tschirhart and E. Potter)

Table 1.1: Aeromagnetic surveys since 2015

Survey Location	Year	Line spacing (m)
Amittok Lake, NU	2015	400
Kluane Lake West, YT	2015	250
McKeand River, NU	2015	400
Frances Lake, YT	2016	400
Livingstone Creek, YT	2016	200
Northern Boothia Peninsula B&C, NU	2016	400

Marguerite River, SK/AB	2017	400
Llewellyn, YK/BC	2017	400
Overby-Duggan, NU	2017	400
MacKenzie mountain, YK	2017	800
Hopedale, NL	2017	200
Keele River, YK	2017	800
Marsh Lake, YK	2017	400

Publications:

Miles, W., Saltus, R., Hayward, N., and Oneschuk, D., 2019. Yukon-Alaska magnetic compilation, residual total field. Geological Survey of Canada, Open File 7862 (revised), 2019, 1 sheet.

Percival, J.A. and Tschirhart, V., 2017, Trans-Hudsonian far-field deformation effects in the Rae foreland: an integrated geological-3D magnetic model. Tectonophysics, 699, 82-92.

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Tschirhart, V. and Pehrsson, S.J., 2016, New insights from geophysical data on the regional structure and geometry of the southwest Thelon Basin and its basement, Northwest Territories, Canada. Geophysics, 81, B167-B178.

Pilkington, M., 2016, Resolution measures for 3-D magnetic inversions: Geophysics, v.81, J15-J23.

Li, X. and Pilkington, M., 2016, Attributes of the magnetic field, the analytic signal, and the monogenic signal for gravity and magnetic interpretation: Geophysics, v.81, J79-J86.

Hayward, N., Corriveau, L., and Enkin, R., 2016. Geophysical study of alteration and mineralisation at the NICO deposit, NT, Canada. Economic Geology.

Kerswill, J.A., Hayward, N., and Oneschuk, D. 2016. Knowledge-driven (KD) prospectivity model for IOCG deposits in the Great Bear Magmatic Zone, Northwest Territories and Nunavut, NTS 85-N and 86-C, F and K, and parts of NTS 85-M and 86-D, E and L. Geological Survey of Canada, Open File 8034, 2016; 1 sheet, doi:10.4095/298693

Kerswill, J.A., Hayward, N., and Oneschuk, D. 2016. Knowledge-driven (KD) prospectivity model for IOCG deposits in the Great Bear Magmatic Zone, Northwest Territories, Parts of

NTS 86-F, G, J and K. Geological Survey of Canada, Open File 8035, 2016; 1 sheet, doi:10.4095/298694.

Hayward, N., 2015. Geophysical investigation and reconstruction of lithospheric structure and its control on geology, structure and mineralization in the Cordillera of northern Canada and eastern Alaska. Tectonics, 34, doi:10.1002/2015TC003871.

Snyder, D.B., Craven, J.A., Pilkington M., and Hillier, M.J., 2015, The 3-D construction of the Rae craton, central Canada, Geochemistry, Geophysics & Geosystems, v.16, 3555–3574.

Tschirhart, V., Percival, J.A. and Jefferson, C.W., 2015, Geophysical models of the Montresor metasedimentary belt and its environs, central Nunavut, Canada. Canadian Journal of Earth Sciences, 52, 833-845.

Evenchick, C.A., Davis, W.J., Bedard, J.H., Hayward, N., Friedman, R.M. 2015. Evidence for protracted High Arctic large igneous province magmatism in the central Sverdrup Basin from stratigraphy, geochronology, and paleodepths of saucer-shaped sills. GSA Bulletin, B31190.1, first published on April 14, 2015, doi:10.1130/B31190.1

2.3 Geomagnetic Magnetic Observatories and Surveys

The Geomagnetic Laboratory of the Geological Survey of Canada operates a network of 14 magnetic observatories in Canada and continues to be active in INTERMAGNET, which represents the global network of geomagnetic observatories. Canada hosts the INTERMAGNET web site through the Geomagnetic Laboratory, providing a useful portal for retrieving data files from the global network.

Geomagnetic Laboratory of the Geological Survey of Canada:
http://www.geomag.nrcan.gc.ca/lab/default-fr.php
http://www.geomag.nrcan.gc.ca/lab/default-en.php
INTERMAGNET web site: www.intermagnet.org

Research is conducted, often in conjunction with industrial or academic partners, on a variety of geomagnetic and space weather hazards to technological systems. These include: modelling of geomagnetically induced currents in power systems; telluric current effects on cathodic protection of pipelines; high energy particle effects on satellites; induction in submarine phone cables; the effects of ionospheric and geomagnetic disturbances on GPS and geophysical exploration techniques.

Space weather forecasting:
NRCan/GSC forecasts for the polar, auroral, and sub-auroral regions of Canada are produced using well-established quantitative algorithms. The forecasts for Canada or for subregions are based on the most recent measured magnetic field data from the observatories in the region, on long term statistical models of the temporal behaviour of the field at that location, and on the latest solar and solar wind data which are provided through collaborations with NOAA and NASA. Space Weather website: www.spaceweather.ca

2.4 École de Technologie Supérieure and Carleton University

(Claire Samson)

Samson's applied geophysics research group over 2015-2019 (at Carleton University, and from January 2018 onwards at ETS) includes students and collaborations investigating autonomous and semi-autonomous magnetic and electromagnetic methods, as carried by rovers, drones and UAVs.

Publications:

Hay, A., Samson, C., Tuck, L., Ellery, A. 2018. Magnetic surveying with an unmanned ground vehicle. Journal of Unmanned Vehicle Systems 6 (4), 249-266

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2.5 Department of Earth, Ocean and Atmospheric Sciences – University of British Columbia

(Catherine L. Johnston)

Ongoing research in the Planetary Sciences Group on IAGA-themed topics includes: the past behaviour of the Earth's geomagnetic field (its paleosecular variation), and the evidence for and implications of planetary and crustal magnetic fields in Mercury and Mars. From 2006-2016 Johnson was a Participating Scientist in the MESSENGER Mission which operated on orbit at Mercury. She was also Vice Chair, Geophysics Group, MESSENGER Science Steering committee (2013-2016). Johnson is currently President (2019-2020) of the Geomagnetism, Paleomagnetism and Electromagnetism (GPE) Section of the American Geophysical Union.

Publications:

Johnson, C. L., B. J. Anderson, H. Korth, R. J. Phillips and L. C. Philpott (2018), Mercury's Internal Magnetic Field, Chapter 5, Mercury from MESSENGER, Cambridge University Press.

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Johnson, C. L., R. J. Phillips, M. E. Purucker, B. J. Anderson, P. K. Byrne, D. W. Denevi, J. M. Feinberg, S. A. Hauck II, J. W. W. Head III, H. Korth, P. B. James, E. Mazarico, G. A. Neumann, L. C. Philpott, M. A. Siegler, N. A. Tsyganenko, S. C. Solomon, Low-altitude Magnetic Field Measurements by MESSENGER Reveal Mercury's Ancient Crustal Field, Science, 348, pp 892-895, 2015.

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Dewey, R. M., D. N. Baker, B. J. Anderson, M. Benna, C. L. Johnson, H. Korth, D. J. Gershman, G. C. Ho, W. E. McClintok, D. Odstrcil, L. C. Philpott, J. M. Raines, D. Schriver, J. A. Slavin, S. C. Solomon, R. M. Winslow, T. H. Zurbuchen. (2015). Improving solar wind modeling at Mercury: Incorporating transient solar phenomena into the WSA-ENLIL model with the Cone extension. J. Geophys. Res., Space Physics, 120, 5667-5685.

3 Paleomagnetism and Rock Magnetism

Compiled by Phil J.A. McCausland, University of Western Ontario, (pmccausl@uwo.ca)
Section contributors as noted.

3.1 Department of Earth Sciences, Memorial University, St. John's, Newfoundland

(Joseph P. Hodych)

Presently my main research interests are centered on rock magnetic properties and their physical origin as well as paleomagnetism and Late Precambrian - Early Paleozoic plate tectonics. Current paleomagnetic work at Memorial University, being done collaboratively with K. Buchan (GSC-Ottawa) and P. McCausland (UWO) is focused on the Late Neoproterozoic record of Laurentia in Quebec and Labrador and the Avalonia terrane in Newfoundland.

A BSc thesis was completed (Langdon, 2016) conducting a paleomagnetic fold test for the latest Ediacaran Crown Hill Formation redbeds in Avalonia, and a MSc is currently underway (S. Farrell) on the paleomagnetic study of ca. 580 Ma volcanics near Grand Bank, Newfoundland, to contribute to the investigation of possible Ediacaran true polar wander as observed from Avalonia. Preliminary results from her thesis were reported at the 2018 EGU meeting (Farrell and Hodych, 2018).

Farrell*, S. and Hodych, J.P. 2018. A paleomagnetic study of ca. 580 Ma volcanics near Grand Bank, Avalon Zone of Newfoundland and implications for true polar wander in the Ediacaran. Geophysical Research Abstracts. Vol. 20, EGU2018-9776.

Buchan, K.L., Hamilton, M.A. and Hodych, J.P. 2015. Ediacaran Paleomagnetism of Well-dated Units in Laurentia and West Avalonia: Implications for Oscillatory TPW, Equatorial Dipoles and Rapid Continental Drift". AGU-GAC-MAC-CGU Joint Assembly, 2015. Abstracts Listing. p.175.

3.2 Research Laboratory in Paleomagnetism and Marine Geology - Université du Québec à Rimouski

(Guillaume St-Onge)

Research performed at the Paleomagnetism and Marine Geology Laboratory mostly uses the various magnetic and physical properties of sedimentary sequences to reconstruct variations in Earth's magnetic field, establish high-resolution chronostratigraphy, and develop proxies for natural hazards and paleoclimate for the Quaternary. This research is currently divided along three themes (references to follow, with student contributions identified with an asterix*):

1) Geomagnetic Field Dynamics

An important part of the research conducted in the laboratory is aimed at reconstructing secular and millennial scale variations of Earth's magnetic field during the Quaternary from marine and lacustrine sediment cores collected in Eastern Canada, the Arctic, Antarctica, Asia and the Southern Hemisphere. These reconstructions are used to determine the high frequency dynamics of Earth's magnetic field, understand rapid geomagnetic field changes and the recent migration of the North Magnetic Pole, but also to determine the influence of the geomagnetic field on the modulation of cosmogenic isotopes such as ^{14}C and ^{10}Be: two isotopes generally associated with solar variability at the centennial to millennial timescales.

2) Sedimentary processes and natural hazards
This theme employs geophysical methods and detailed sediment core analysis via cryogenic magnetometer, magnetic susceptibility, core imaging, CT imaging and XRF analyses to investigate the sedimentary processes of several marine and lacustrine areas around the globe. The research is also aimed at identifying, distinguishing and dating sedimentary sequences associated with natural hazards such as landslides, floods and earthquakes during the Quaternary in Eastern Canada, the Arctic and the Southern Hemisphere. The goal is to determine the natural frequency of such natural hazards.

3) Quaternary stratigraphy and climatic changes
Part of the research conducted in the laboratory is aimed at establishing the Quaternary stratigraphy of marine and lacustrine sedimentary sequences from both hemispheres: Eastern Canada, the Arctic and Patagonia. This work is based on high-resolution magnetostratigraphy, but also on the acquisition and interpretation of long sedimentary sequences, as well as seismic and bathymetric profiles acquired in collaboration with several researchers and institutions (e.g, GEOTOP, ArcticNet, Geological Survey of Canada, IODP, ICDP). The students and researchers of the laboratory also use the magnetic and physical properties of the sediment to develop high-resolution tracers of Quaternary climatic and environmental changes.

Laboratory website: https://paleomag.uqar.ca/

Publications:
Penkrot, M., Jaeger, J.M., Cowan, E.A., St-Onge, G., LeVay, L. accepté sous réserve de modifications. Multivariate modeling of glacimarine lithostratigraphy combining scanning XRF, multisensory core properties, and CT imagery: IODP Site U1419. Geosphere.

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Lisé-Pronovost*, A., St-Onge, G., Gogorza, C., Haberzettl, T., Jouve, G., Francus, P., Ohlendorf, C., Gebhardt, C., Zolitschka, B. et l'équipe scientifique PASADO. 2015. Rock-magnetic proxy of wind intensity since 51 200 cal BP from the sediments of Laguna Potrok Aike in southern Patagonia. Earth and Planetary Science Letters 411, 72-86.

Haberzettl, T., Henkel*, K., Kasper, T., Ahlborn, M., Su, Y., Appel, E., St-Onge, G., Stoner, J., Daut, G., Wang, J., Zhu, L., Mäusbacher, R. 2015. Independently dated paleomagnetic secular variation curves from the Tibetan Plateau. Earth and Planetary Science Letters 416, 98–108.

Recasens, C., Ariztegui, D., Maidana, N.I., Zolitschka, B. et l'équipe scientifique PASADO (incluant St-Onge, G. et Lisé-Pronovost*, A.) 2015. Diatoms as indicators of hydrological and climatic changes in Laguna Potrok Aike (Patagonia) since the Late Pleistocene. Palaeogeography, Palaeoclimatology, Palaeoecology 417, 309-319.

3.3 Geological Survey of Canada - Ottawa

(Kenneth L. Buchan)

Paleomagnetic studies are continuing on precisely-dated diabase dyke swarms of Laurentia (in collaboration with M. Hamilton and T. Sahin of the University of Toronto, R. Ernst of Carleton and Tomsk Universities, and other colleagues). Paleomagnetic studies of magmatic and sedimentary rocks of West Avalonia are ongoing with J. Hodych (Memorial University). Collaborative work is also being conducted with R. Ernst to document giant radiating and circumferential dyke swarms around the globe, and to compare circumferential swarms with circular tectonomagmatic features on Venus called coronae.

Publications:

Buchan, K.L., and Ernst, R.E. 2019. Giant circumferential dyke swarms: Catalogue and characteristics. In: Srivastava, R.P., Ernst, R.E., and Peng, P. (eds.), Dyke swarms of the World: A modern perspective. Springer Geology, Springer, Singapore, p. 1-44.

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Ernst, R.E., Hamilton, M.A., Söderlund, U., Hanes, J.A. Gladkochub, D.P., Okrugin, A.V., Kolotilina, T., Mekhonoshin, A.S., Bleeker, W., LeCheminant, A.N., Buchan, K.L., Chamberlain, K.R., Didenko, A.N. 2016. Long-lived connection between southern Siberia and northern Laurentia in the Proterozoic. Nature Geoscience 9: 464-469. With 33p. Supplementary Information file DOI: 10.1038/NGEO2700

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Conference presentations:

Buchan, K.L., Hamilton, M.A., and Hodych, J.P. 2015. Ediacaran paleomagnetism of well-dated units in Laurentia and West Avalonia: implications for models of oscillatory true polar wander, equatorial dipoles and rapid continental drift. Joint AGU-GAC-MAC-CGU, Abstracts Listing, p. 175.

Buchan, K.L., and Ernst, R.E. 2015. A giant circumferential dyke swarm associated with the High Arctic Large Igneous Province (HALIP) – a possible analogue for coronae on Venus. Joint AGU-GAC-MAC-CGU, Abstracts Listing, p. 366..

3.4 Department of Earth Sciences – Carleton University

(Richard E. Ernst)

My focus is Large Igneous Provinces (LIPs), which represents an extreme type of volcanism that occurs on Earth on average every 20-30 million years and results in breakup of continents, dramatic changes in climate and is linked to many major types of ore deposits.

Current activities at Carleton, and as Guest Professor at Tomsk State University, Tomsk, Siberia Russia include:

1) Compiling a global LIP map for Earth (for the CGMW: Commission for the Geological Map of the World) (in progress)

2) Leading the LIPs Commission of IAVCEI and maintaining the Commission website www.largeigneousprovinces.org

3) The Large Igneous Province (LIP) Record of Russia Through Time: Preliminary Summary http://www.largeigneousprovinces.org/18dec

4) Research via an industry-academic consortium towards reconstructing Precambrian supercontinents using refined geochronology, paleomagnetic and geochemical data.

Research website: http://research.earthsci.carleton.ca/ernst-lab

Convened Conference Sessions:

Ernst, R.E. and Jowitt, S.M. (2018) MIN11: Multi-Commodity, Multi-Scale Exploration Targeting Using the Large Igneous Province Record. Resources for Future Generations Conference (RFG 2018), June 16-21, 2018, Vancouver, Canada, http://www.rfg2018.org/

Zhang, F-F., Al-Suwaidi, A., Ernst, R., Cui, Y. 2018 04h: Large Igneous Provinces, Environmental Change and Mass Extinctions: The Deadly Kiss of LIPs. Goldschmidt 2018 August 12-17, Boston, USA, https://goldschmidt.info/2018/

Kingsbury, C., R.E. Ernst (2017) Chemical Scene Investigations of Large Igneous Provinces II GSA Annual meeting, Seattle USA (22-25 October)

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Williamson, M-C., C. Lawley, D. Giovenazzo, S. Planke, S. Bergman, R. Ernst (2017) GAC-MAC annual meeting 2017 GS1: Magmatic and Metallogenic Processes Associated with Large Igneous Provinces (LIPs) Kingston Ontario, May 14-18

Ernst, R.E., Bekker, A., Al-Suwaidi, A., Dickson, A. (2017) Session 17l: Deadly kiss of LIPs: Their role in Phanerozoic and Precambrian environmental change and biotic exctinctions. Goldschmidt Conference, Paris, France, 13 - 18 August 2017

Gregg, T., R. Ernst (2016). T166: Large Igneous Provinces (LIPs) in the Solar System. Geological Society of America Annual meeting, Denver, 25-28 Sept 2016.

Jowitt, S., R. Ernst (2016) Links between Large Igneous Province Events and Metallogeny, session 9b. Goldschmidt 2016 Yokohama, Japan, 26 June – 1 July 2016.

Xu, Y-G., I. Campbell, R. Ernst, C. Yang (2016) Large Igneous Provinces Through Time: Their Origin and Economic/Environmental Impacts, session 5d, Goldschmidt 2016, Yokohama, Japan, 26 June – 1 July 2016.

Ernst, R.E., C. Kingsbury, & P. Hollings (2015). CSI-LIPs (Chemical scene investigation of Large Igneous Provinces). Session VGP32A Joint Assembly (AGU-GAC-MAC-CGU) meeting Montreal (3-7 May 2015).

Ernst, R.E., & D. Hurwitz (2015). Surface Expressions of Volcanism and Associated Tectonism on Venus and Implications for Interior Dynamics. Session P42 Joint Assembly (AGU-GAC-MAC-CGU) meeting Montreal (3-7 May 2015).

Evans, D.A.D., & R.E. Ernst (2015). Precambrian Craton Reconstructions, Geodynamics, and Paleoenvironments. Session PG23A Joint Assembly (AGU-GAC-MAC-CGU) meeting Montreal (3-7 May 2015).

Selected Keynote Talks:

June 2018: Resources for Future Generations Conference (RFG2018), Vancouver, Canada: Keynote on first day of conference (Monday June 18) Ernst, R.E. "Importance of Earth's Geological History for Understanding Modern Climate Change"; http://www.rfg2018.org/en/RFG/2018/Technical-Program/Plenaries

August 2017: International Conference on Large Igneous Provinces, Chengdu University of Technology, China (August 26 to 31, 2017). Ernst, R.E. "Frontiers in Large Igneous Province Research"

April 2017: Target 2017 Meeting April 19-21, Perth Australia: Ernst, R.E., Jowitt, S.M. "Multi-commodity, multi-scale exploration targeting using the Large Igneous Province Record" http://target2017.org.au/program/keynote-speakers/

November 2015: Keynote in Mass Extinction Session at GSA 2015 Annual Meeting: Ernst, R.E. "How Large Igneous Provinces affect climate and sometimes cause extinctions" Keynote talk in Session T153: Mass Extinction Causality: Records of Anoxia, Acidification, and Global Warming during Earth's Greatest Crises at GSA 2015 Annual Meeting Baltimore, GSA Press Release on my Keynote Presentation

Refereed book chapters:

Baratoux, L., Söderlund, U., Ernst, R.E., de Roever, E., Jessell, M.W., Kamo, S., Naba, S., Perrouty, S., Metelka, V., Yatte, D., Grenholm, M., Diallo, D.P., Ndiaye, P.M., Dioh, E., Cournède, C., Benoit, M., Baratoux, D., Youbi, N., Bendaoud, A. (2018) New U-Pb baddeleyite ages of dolerite dyke swarms between 1791 Ma and 200 Ma, Leo-1 Man Craton, West Africa, and link with the Guiana Shield, South America. In: Srivastava, R.K., Ernst, R.E., Peng, P. (eds.) Dyke Swarms of the World – A Modern Perspective. Springer (in press)

Magee, C., Ernst, R.E., Muirhead, J., Phillips, T., Jackson, C. A-L. (2018). Magma Plumbing Systems in Large Igneous Provinces: Lessons from Seismic Reflection Data. In: Srivastava, R.K., Ernst, R.E., Peng, P. (eds.) Dyke Swarms of the World – A Modern Perspective. Springer (in press)

Hollanda, M.H.B.M., Archanjo, C.J., Macedo Filho, A.A., Fossen, H., Ernst, R.E., de Castro, D.L., Melo, A.C., Oliveira, A.L. (2018) The Mesozoic Equatorial Atlantic Magmatic Province (EQUAMP): A new large igneous province in South America. In: Srivastava, R.K., Ernst, R.E., Peng, P. (eds.) Dyke Swarms of the World – A Modern Perspective. Springer (in press)

Samal, A.K., Srivastava, R.K., Ernst, R.E., Söderlund, U. (2018) Mapping and naming of distinct Neoarchean-Mesoproterozoic mafic dyke swarms of the Indian Shield using Google™ Earth images and ArcGIS™ and their possible association to Large Igneous Provinces: current status and future prospects. In: Srivastava, R.K., Ernst, R.E., Peng, P. (eds.) Dyke Swarms of the World – A Modern Perspective. Springer.

Rogers, C., A. Mackinder, R.E. Ernst, & B. Cousens (2016). Mafic magmatism in the Belt-Purcell Basin and Wyoming Province of Western Laurentia. In: J. MacLean & J. Sears (eds.) Belt Basin: Window to Proterozoic Earth: Geological Society of America Special Paper.

Evans, D.A.D., R.I.F. Trindade, E.L. Catelani, M.S. D'Agrella-Filho, L.M. Heaman, E.P. Oliveira, U. Söderlund, U., R.E. Ernst, A.V. Smirnov, & J.M. Salminen (2016). Return to Rodinia? Moderate to high paleolatitude of São Francisco/Congo craton at 920 Ma: In: Li, Z.X., D.A.D. Evans & J.B. Murphy (eds,): Supercontinent Cycles Through Earth History Geological Society of London Special Publication 424. doi:10.1144/SP424.1, p. 167-190.

Publications:

Rogers, C., Kamo, S.L., Soderlund, U., Hamilton, M.A., Ernst, R.E., Cousens, B., Harlan, S.S., Wade, C.E., Thorkelson, D.J. (2018) Geochemistry and U-Pb geochronology of 1590 and

1550 Ma mafic dyke swarms of Western Laurentia: Mantle plume magmatism shared with Australia. Lithos (in press).

Teixeira, W., Hamilton, M.A., Girardi, V.A.V., Faleiros, F.M., Ernst, R.E. (2018). U-Pb baddeleyite ages of key dyke swarms in the Amazonian Craton (Carajás/Rio Maria and Rio Apa areas): tectonic implications for events at 1880, 1110 Ma, 535 Ma and 200 Ma. Precambrian Research (in press)

Ni, N., Chen, N-h., Ernst, R.E., Yang, S-f., Chen, J-n. (2018). Semi-automatic extraction and mapping of dyke swarms based on multi-resolution remote sensing images: Applied to the dykes in Kuluketage region in the northeastern Tarim Block. Precambrian Research (in press).

El Bahat A., Ikenne, M., Cousens, B., Söderlund, U., Ernst, R. Klausen, M.B. Youbi, N. (2017) New constraints on the geochronology and Sm-Nd isotopic characteristics of Bas-Drâa mafic dykes, Anti-Atlas of Morocco. Journal of African Earth Sciences, v. 127, p. 77-87.

Kingsbury, C.G., Kamo, S.L., Ernst, R.E., Soderlund, U., Cousens, B.L. (2017) U-Pb geochronology of the plumbing system associated with the Late Cretaceous Strand Fiord Formation, Axel Heiberg Island, Canada. Journal of Geodynamics, v. 118, p. 106-117.

Beraaouz, M., Macadam, J., Bouchaou, L., Ikeen, M., Ernst, R., Tagma, T., Masrour, M. (2017) An inventory of geoheritage sites in the Draa valley (Morocco): A contribution to promotion of geotourism and sustainable development. Geoheritage, doi: 10.1007/s12371-017-0256-x

Ernst, R.E., N. Youbi (2017). How Large Igneous Provinces affect global climate, sometimes cause mass extinctions, and represent natural markers in the geological record. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 478, p. 30-52.

Ciborowski, T.J.R., M.J. Minifie, A.C. Kerr, R.E. Ernst, B. Baragar, I.L. Millar. 2017. A mantle plume origin for the Palaeoproterozoic Circum-Superior Large Igneous Province. Precambrian Research, 294, 189-213

Zhang, S.H., Y. Zhao, X.H. Li, R.E. Ernst, Z.Y. Yang. 2017. The 1.33-1.30 Yanliao large igneous province in the North China Craton: Implications for reconstruction of the Nuna (Columbia) supercontinent, and specifically with the North Australian craton. Earth and Planetary Science Letters, v. 465, p. 112-125.

Shumlyanskyy, L., C. Hawkesworth, K. Billström, S. Bogdanova, O. Mytrokhyn, R. Romer, B. Dhuime, S. Claesson, R. Ernst, M. Whitehouse, O. Bilan. 2017. The origin of the Palaeoproterozoic AMCG complexes in the Ukrainian shield. New U-Pb ages and Hf isotopes in zircon. Precambrian Research, v. 292 p 216-239.

El Bahat, A., M. Ikenne, B. Cousens, U. Söderlund, R. Ernst, M.B. Klausen, N. Youbi (2017). New constraints on the geochronology and Sm-Nd isotopic characteristics of Bas Drâa mafic dykes, Anti-Atlas of Morocco. Journal of African Earth Sciences, v. 127, p. 77-87, doi: 10.1016/j.jafrearsci.2016.09.003

Ikenne, M., U. Söderlund, R.E. Ernst, C. Pin, N. Youbi, E. El Aouli, A. Hafid (2017). A c. 1710 Ma mafic sill emplaced into a quartzite and calcareous series from Ighrem, Anti-Atlas – Morocco: Evidence that the Taghdout passive margin sedimentary group is nearly 1 Ga older than previously thought. Journal of African Earth Sciences, 127, p. 62-76, doi: 10.1016/j.jafrearsci.2016.08.020

Blanchard, J.A., Ernst, R.E., Samson, C. (2017) Gravity and magnetic modelling of layered mafic-ultramafic intrusions in large igneous province plume centre regions; Case studies from the: 1.27 Ga Mackenzie, 1.38 Ga Kunene-Kibaran, 0.06 Ga Deccan and 0.13-0.08 Ga High Arctic events. Canadian Journal of Earth Sciences, v. 54, p. 290-310, doi: 10.1139/cjes-2016-0132.

Shumlyanskyy, L., R.E. Ernst, K. Billstrom, B.A. Wing, A. Bekker (2016) Age and sulfur isotope composition of the Prutivka intrusion (the 1.78 Ga Prutivka-Novogol Large Igneous Province in Sarmatia). Mineralogical Journal: Geochemistry (Ukraine), v. 38, no. 3, p. 91-101.

Ernst, R.E,.M.A. Hamilton, U. Söderlund, J.A. Hanes, D.P. Gladkochub, A.V. Okrugin, T. Kolotilina, A.S. Mekhonoshin, W. Bleeker, A.N. LeCheminant, K.L. Buchan, K.R. Chamberlain, A.N. Didenko (2016) Long-lived connection between southern Siberia and northern Laurentia in the Proterozoic. Nature Geoscience, v. 9, p. 464-469, doi: 10.1038/NGEO2700 [see coverage in media file].

Kingsbury, C., R.E. Ernst, B.L., Cousens, M-C. Williamson (2016) The High Arctic LIP in Canada: Trace element and Sm-Nd Isotopic evidence for the role of mantle heterogeneity and crustal assimilation. Norwegian Journal of Geology, (in press), doi.org/10.17850/njg96-2-02.

Petrov, O., A. Morozov, S. Shokalsky, S. Kashubin, I.M. Artemieva, N. Sobolev, E. Petrov, R.E. Ernst, S. Sergeev, M. Smelror (2016). Crustal structure and tectonic model of the Arctic region. Earth-Science Reviews, v. 154, p. 29–71.

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Gladkochub D.P., Donskaya T.V., Mazukabzov A.M., Pisarevskyi S.A., Ernst R.E., Stanevich A.M. (2016) Mesoproterozoic mantle plume beneath the northern part of the Siberian craton. Russian Geology and Geophysics, v. 57, p. 672-686.

Mekhonoshin, A.S., R.E. Ernst, U. Söderlund, M. A. Hamilton, T.B. Kolotilina, A.E. Izokh, G.V. Polyakov, N.D. Tolstykh (2016) Relationship between platinum-bearing ultramafic–mafic intrusions and large igneous provinces (exemplified by the Siberian Craton). Russian Geology and Geophysics, v. 57, p. 822-833.

Ernst, R.E., A.V. Okrugin, R.V. Veselovskiy, S.L. Kamo, M.A. Hamilton, V. Pavlov, U. Söderlund, K.R. Chamberlain, C. Rogers (2016). The 1501 Ma Kuonamka Large Igneous Province of northern Siberia: U-Pb geochronology, geochemistry, and links with coeval magmatism on other crustal blocks. Russian Geology and Geophysics, v. 57, p. 653-671.

Puchkov, V., R.E. Ernst, M.A. Hamilton, U, Söderlund, N. Sergeeva. (2016) A Devonian >2000-km long dolerite swarm-belt and associated basalts along the Urals-Novozemelian fold-belt: part of an East-European (Baltica) LIP tracing the Tuzo Superswell. GFF, v. 138, p. 6-16, 10.1080/11035897.2015.1118406.

Lubnina, N.V., A.V. Stepanova, R.E. Ernst, M. Nilsson, U. Söderlund (2016) New U–Pb baddeleyite age, and AMS and paleomagnetic data for dolerites in the Lake Onega region belonging to the 1.98–1.95 Ga regional Pechenga-Onega Large Igneous Province. GFF, v. 138, p. 54-78, doi: 10.1080/11035897.2015.1129549.

Shumlyanskyy, L., R.E. Ernst, U. Söderlund, K. Billström, O. Mitrokhin, and S. Tsymbal (2016) New U-Pb ages for mafic dykes in the Northwestern region of the Ukrainian shield: coeval tholeiitic and jotunitic magmatism. GFF, v. 138, p. 79-85, doi: 10.1080/11035897.2015.1116602.

Shumlyanskyy, L., O. Mitrokhin, K. Billström, R. Ernst, E. Vishnevska, S. Tsymbal, M. Cuney, A. Soesoo (2016). The ca. 1.8 Ga mantle plume related magmatism of the central part of the Ukrainian shield. GFF, v. 138, p. 86-101, doi: 10.1080/1331677X.2015.1067253.

Cederberg, J., U. Söderlund, E.P. Oliveira, R.E. Ernst, & S.A. Pisarevsky (2016) U-Pb baddeleyite dating of the Proterozoic Pará de Minas dyke swarm in the São Francisco craton (Brazil) – implications for tectonic correlation with Siberian, Congo and North China cratons. GFF, v. 138, p. 219-240, doi: 10.1080/11035897.2015.1093543.

Teixeira, W., R.E. Ernst, M.A. Hamilton, G. Lima, A.S. Ruiz, M.C. Geraldes (2016). Widespread ca. 1.4 Ga intraplate magmatism and tectonics in a growing Amazonia. GFF, v. 138, p. 241-254, doi: 10.1080/11035897.2015.1042033.

Li, H-B., Z-C. Z. L-S. Lu, R.E. Ernst, M. Santosh, D-Y. Zhang, & Z-G. Cheng (2015). Giant radiating mafic dyke swarm of the Emeishan Large Igneous Province: Identifying the mantle plume centre: Terra Nova, v. 27, no. 4, p. 247–257, doi: 10.1111/ter.12154.

Shumlyanskyy L., R. Ernst, & K.A. Billström (2015). U-Pb baddeleyite age of the Davydky gabbro-syenite massif of the Korosten plutonic complex: Geochemistry and ore formation, v. 35, p. 37-42.

Ciborowski, T.J.R., A.C. Kerr, R.E. Ernst, I. McDonald, M.J. Minifie, S.S. Harlan, & I.L. Millar (2015). The Early Proterozoic Matachewan Large Igneous Province: Geochemistry, Petrogenesis, and Implications for Earth Evolution: Journal of Petrology, v. 56 (8), p. 1459-1494, doi: 10.1093/petrology/egv038.

Thórarinsson, S.B., U. Söderlund, A. Døssing, P.M. Holm, R.E. Ernst, & C. Tegner (2015). Rift magmatism on the Eurasia basin margin: U-Pb baddeleyite ages of alkaline dyke swarms in North Greenland: Journal of the Geological Society, v. 172:721-726, doi:10.1144/jgs2015-049.

Jessell, M., J. Santoul, L. Baratoux, N. Youbi, R.E. Ernst, V. Metelka, J. Miller, & S. Perrouty (2015). An updated map of West African mafic dykes: Journal of African Earth Sciences. 10.1016/j.jafrearsci.2015.01.007.

Pisarevsky, S.A., De Waele, B., Jones, S., Söderlund, U. and Ernst, R.E. (2015). Paleomagnetism and U-Pb age of the 2.4 Ga Erayinia mafic dykes in the south-western Yilgarn, Western Australia: paleogeographic and geodynamic implications: Precambrian Research, v. 259, p. 222-231, doi: 10.1016/j.precamres.2014.05.023.

3.5 Department of Earth Sciences, University of Toronto

(Henry C. Halls)

Recent Paleomagnetic research at the Paleomagnetic Laboratory:

1) Paleomagnetic sampling of a transect through the Grenville orogeny in Ontario was done, recovering distinct directional patterns north (in the parautochthon) and south (in the allochthon) of the Allochthon Boundary Thrust (ABT) in the Grenville province (Halls, 2015). The newly discovered shallow, high unblocking temperature and high coercivity paleomagnetic directions in the parautocthon and much steeper directions observed in this study and elsewhere in the Grenville allochthon suggest that there may once have been a significant distance between them, now accomodated across the ABT. Followup field and laboratory research is underway to further explore this phenomenon.

2) A major summary analysis of the ca. 585 Ma Grenville Dyke swarm's western end in Ontario, including new U-Pb geochronology, geochemistry and paleomagnetic sampling, has shown evidence for primary remanence for dykes with steep remanence and those with shallow remanence, within an overall span of <10 million years. This result implies that the recorded directional changes may require a modification of the Geocentric Axial Dipole (GAD) assumption for the general time-averaged geometrical behaviour of the Earth's geodynamo; implied apparent poilar motion to too rapid to accommodate with True Polar Wander or rapid plate motions, and instead suggests that the Earth's field may have been in transition between multiple reversals for much of the mid-Ediacaran (Halls et al., 2015).

International Dyke Conference

The most recent meeting of the International Dyke Conference (series founded by myself in 1985) was held on 18-20 August, 2016 in Beijing, China, as IDC7. I was invited to IDC7 as an honourary guest. The IDC series continues, with the next meeting in Marrakesh, Morocco, in 2020.

Publications:

Westgate, J.A., Gabriel, G.W., Halls, H.C., Bray, C.J., Barendregt, R.W., Pearce, N.J.G., Sarna-Wojcicki, A.M., Gorton, M.P., Kelley, R.E. and Schultz-Fellenz, E. 2018. Quaternary tephra from the Valles caldera in the volcanic field of the Jemez Mountains of New Mexico identified in Western Canada. Quaternary Research, 86

Halls, H.C. 2015. Paleomagnetic evidence for ~4000km of crustal shortening across the 1Ga Grenville orogen of North America. Geology, 43, 1051-1054

Halls, H.C., Lovette, A., Hamilton, M.A., Söderlund, U. 2015. A paleomagnetic and U-Pb geochronology study of the western end of the Grenville dyke swarm: rapid changes in

paleomagnetic field direction at ca. 585 Ma related to polarity reversals? Precambrian Research, 257,137-166.

3.6 McMaster University

(W. (Bill) A. Morris)

Current research includes the application of potential field geophysics and remote sensing techniques to mineral and oil exploration problems; Potential field modelling and image analysis; Three Dimensional geological and non-seismic geophysical modelling; Data integration and remote predictive geological mapping; Borehole magnetics surveys for navigation; and subsurface geological modelling; Application of paleomagnetic, and physical rock property techniques for applications in oil and mineral exploration.

In the past four years some of my major contributions have been as Head of Data Integration for the NSERC-Canadian Mining Innovation Council – Mineral Exploration Footprints Project, which is a major industry-academic collaboration. http://cmic-footprints.laurentian.ca/

Short course:

"Improving Exploration with Petrophysics: The Application of Magnetic Remanence and Other Rock Physical Properties to Geophysical Targeting" (R. J. Enkin and W.A. Morris), Exploration '17, Decennial Mining Exploration Conference, Toronto, October 2017.

Publications:

Ugalde, H., Morris, W.A., and van Staal, C. 2018. The Bathurst Mining Camp, New Brunswick: 3D Modeling results and implications for exploration. Canadian Journal of Earth Sciences. Accepted for Publication.

Morris, W.A., Underhay, S-L., Ugalde, H. and Milkereit, B. 2018. Borehole Magnetic surveys in weakly magnetic sediments (Chicxulub impact crater) versus strongly magnetic volcanics (Bathurst Mining Camp). Canadian Journal of Earth Sciences. Accepted for publication.

Tschirhart, P., Morris, W.A., Mims, J. and Ugalde, H. 2018. Applying laterally varying density corrections to ground gravity and airborne gravity gradiometry data. A case study from the Bathurst Mining Camp. Canadian Journal of Earth Sciences. Accepted for publication.

Lesage, G., Byrne, K., Morris, W.A., Enkin, R.J., Lee, R., Mir, R. and Hart, C.J.R. 2018. A new method for district-scale 3D fault network interpretation using combined geological and geophysical data at Highland Valley Copper, British Columbia. Journal of Structural Geology accepted for publication.

Byrne, K., Lesage, G., Morris, W.A., Enkin, R.J. and Gleeson, S.A. Variability of outcrop magnetic susceptibility and its relationship to the porphyry Cu deposits at Highland Valley Copper. Ore Geology reviews. Accepted for publication

Berube, C.L., Olivo, G.R., Chouteau, M., Perrouty, S., Shamsipour, P., Enkin, R.J., Morris, W.A., Feltrin, L. and Thiemonge, R. 2018. Predicting rock type and detecting hydrothermal alteration using machine learning and petrophysical properties of the Canadian Malartic

ore and host rocks, Pontiac Subprovince, Quebec, Canada.Ore Geology Reviews, 96, 130 – 145.

Tschirhart, V., Jefferson, C.W., and Morris, W.A., 2017. Basement geology beneath the northeast Thelon Basin, Nunavut: Insights from integrating new gravity, magnetic and geologic data. Geophysical Prospecting, 65(2), 617 – 636.

Perrouty, S., Gaillard, N., Piette-Lauzière, N. Mir, R., Bardoux, M. Olivo, G.R., Linnen, R.L., Bérubé, C.L., Lypaczewski, P., Guillmette, C., Feltrin, L. and Morris., W.A. 2017. Structural setting for Canadian Malartic style of gold mineralization in the Pontiac Subprovince, south of the Cadillac Larder Lake Deformation Zone, Québec, Canada. Ore Geology Reviews, 84, 185 - 205.

Tschirhart, P., and Morris, W.A., 2015. Improved edge detection mapping through stacking and integration: A case study in the Bathurst Mining Camp. Geophysical Prospecting, 63(2), 283-295.

Selected conference abstracts:

Morris, W.A., Tschirhart, V., Jefferson, C. and Ugalde, H. "Fracture framework mapping from magnetics: The Schultz Lake Igneous Complex" Resources for Future Generations Conference (RFG 2018), June 16-21, 2018, Vancouver, Canada, http://www.rfg2018.org/

Morris, W.A., Underhay, S-L., Lenauer, I. and Ugalde, H. "Preservation and Deformation of an ancient impact crater: The Sudbury Impact Structure" Resources for Future Generations Conference (RFG 2018), June 16-21, 2018, Vancouver, Canada, http://www.rfg2018.org/

Furlan, A., Ugalde, H., Morris, W.A., Milkereit, B., Mirza, A. and Elliott, B. 2018. "Remote Sensing and High-Resolution Dem Data Integration of Slave Province Kimberlites, NWT" Resources for Future Generations Conference (RFG 2018), June 16-21, 2018, Vancouver, Canada, http://www.rfg2018.org/

Ugalde, H., Furlan, A., Morris, W.A., Milkereit, B., Mirza, A. and Elliott, B. 2018. "Airborne MAG/EM Data Integration of Slave Province Kimberlites, NWT" Resources for Future Generations Conference (RFG 2018), June 16-21, 2018, Vancouver, Canada, http://www.rfg2018.org/

Ugalde, H., Morris, W.A., van Staal, C. and Tschirhart, P. 2018. "The Bathurst Mining Camp, New Brunswick, Canada: 3D integration of geophysical data and implications for exploration" Resources for Future Generations Conference (RFG 2018), June 16-21, 2018, Vancouver, Canada, http://www.rfg2018.org/

Morris, W.A., Underhay, S-L., Ugalde, H. and Milkereit, B. 2018. "Borehole Magnetic surveys in weakly magnetic sediments (Chixculub impact crater) versus strongly magnetic volcanics (Bathurst Mining Camp)" Resources for Future Generations Conference (RFG 2018), June 16-21, 2018, Vancouver, Canada, http://www.rfg2018.org/

Morris, W.A., Ugalde, H., Enkin, R.J. and Valee, M. 2018. "Magnetic anomaly constrained inversions and magnetic petrophysics: susceptibility, remanence and viscous" Resources for Future Generations Conference (RFG 2018), June 16-21, 2018, Vancouver, Canada, http://www.rfg2018.org/

Morris, W.A., Tschirhart, V. and Jefferson, C.W. 2017. Fracture framework mapping from magnetics: a SLIC example. SAGA Conference, Capetown, South Africa

3.7 Western Paleomagnetic and Petrophysical Laboratory – University of Western Ontario

(Phil J.A. McCausland)

Current research in the Western Paleomagnetic and Petrophysical Laboratory is arranged along four themes, and over the past four years has involved eight graduate student theses (students listed with each theme).

1) Paleogeography of the Earth: determining the Earth's Precambrian-Paleozoic paleogeography via paleomagnetic and other techniques, as a context for understanding extreme paleoclimates, burgeoning life, and as a tracer of global geodynamics (A. Thomson, M. MacRae). Current research is in collaboration with M. Higgins (UQAC), S. Pisarevsky (Curtin), D. Evans (Yale), M. Hamilton (U Toronto), H. Halls (U Toronto), F Jourdan (Curtin), C Hall (U Michigan), J. Jin (UWO) and C. Tsujita (UWO).

2) Tectonics of accretionary orogens and mountain belts: paleomagnetic tracking of the collision, obduction and lateral motion of crustal fragments –terranes– to investigate the mechanisms of their assembly into mountain belts (H. Warsame). This research in Atlantic Canada and Yukon is in collaboration with J. Waldron (U Alberta), B. Murphy (St. FX), D. Symons (U Windsor), J. Hodych (Memorial), S. Barr (Acadia), and G. Dunning (Memorial).

3) Shock metamorphism and parent body processes in the Early Solar System: investigation of the mineralogy and petrology of meteorites as recorders of impact shock deformation, redox processes and small body evolution (D. Uribe, Y. Li). This reseach uses petrophysical techniques along with in situ X-ray diffraction and X-ray CT imaging, in collaboration with R. Flemming (UWO), M. Izawa (Okayama), C. Samson (ETS), D. Holdsworth (UWO), C. Charles (TRIUMF) and P. Brown (UWO).

4) Petrophysical properties: investigation of mineralogy, density, porosity, magnetic, electrical and acoustic properties of ore deposits and their host rocks, as a guide for mineral exploration (E. Fernandes, H. Gunawardana, S. Sara). Current research is in collaboration with D. Good (UWO), B. Morris (McMaster).

Laboratory website: http://www.uwo.ca/earth/research/research_facilities/wppl.html

Convened Conference Sessions:

McCausland, P.J.A. and Ferguson, I. (2018) Geophysical Constraints on Lithospheric Structures and Processes. Resources for Future Generations Conference (RFG 2018), June 16-21, 2018, Vancouver, Canada, http://www.rfg2018.org/

McCausland, P.J.A., Currie, C. and Darbyshire, F. (2018) Solid Earth Geophysics: All for one and one for all! Canadian Geophysical Union annual meeting, June 9-12, 2018, Niagara Falls, Canada, https://meeting2018.cgu-ugc.ca/

Publications:

Jenkins*, L.E., Flemming, R.L. and McCausland, P.J.A. (in press). Quantitative in situ XRD Measurement of Shock Metamorphism in Martian Meteorites: Lattice Strain and Strain-Related Mosaicity in Olivine. Meteoritics and Planetary Science.

Oliver, P., Ralchenko, M., Samson, C., Ernst, R.E., McCausland, P.J.A., West, G.F. 2018. Enhanced nondestructive characterization of ordinary chondrites using complex magnetic susceptibility measurements. Meteoritics and Planetary Science, v. 53, p. 433–447, doi, 10.1111/maps.13028

Fry, C., Samson, C., McCausland, P.J.A., Herd, R.K., Ralchenko, M. and McLeod, T.K. 2018. Iron meteorite bulk densities determined via 3D laser imaging, Meteoritics and Planetary Science v 53, doi: 10.1111/maps.13067

Charles, C.R.J., Robin, P., Davis, D.W. and McCausland, P.J.A. 2018. The 3D structure of metal shells in armoured chondrules from the NWA 801 CR2 chondrite. Meteoritics and Planetary Science v 53, pp 935-951, doi: 10.1111/maps.13038

Symons, D.T.A., Kawasaki, K, McCausland, P.J.A. and Hart, C.J.R. 2016. Paleopole for the 69 Ma Prospector Mountain Stock: A critique of the Carmacks / "Baja BC" transport estimate for Yukon, Canada. Geophysical Journal International v 208, pp 349–367, doi: 10.1093/gji/ggw398

Nasir, S., Al-Rawas, A., Herd, C., Banerjee, N., Ali, A. and McCausland, P.J.A. 2015. Characterization of Oman Meteorites. Sultan Qaboos University, Office of the Deputy Vice-Chancellor for Graduate Studies and Research, Earth Science Research Centre and College of Science, SR/SCI/ETHS/12/01.

Symons, D.T.A., McCausland, P.J.A.. Kawasaki, K. and Hart, C.R. 2015. Post-Triassic para-autochthoneity of the Yukon-Tanana Terrane: Paleomagnetism of the Early Cretaceous Quiet Lake Batholith. Geophysical Journal International, v 203, pp 312–326, doi: 10.1093/gji/ggv296

Selected Conference Abstracts:

McCausland, P.J.A., Higgins, M., Pisarevsky, S., Jourdan, F. Hamilton, M., LeCheminant, A. and Murphy, J.B. 2019. Laurentia during the mid Ediacaran: Paleomagnetism and 580 Ma age of the Saint-Honoré alkali intrusion and dykes, Quebéc. GAC-MAC Annual meeting, Quebéc, May 2019.

Li*, Y, McCausland, P.J.A. and Flemming, R.L. 2018. Quantification of shock stages in ureilite olivine by in-situ micro-X-ray diffraction. Lunar and Planetary Science Conference XLIX, Houston, TX. March, 2018.

McCausland, P.J.A. 2017. Assembly of the Northern Cordillera: Mesozoic to present terrane motions and their evolving relationship with North America. CGU Annual Meeting, Vancouver, BC, May, 2017.

McCausland. P.J.A., Deng*, M., Umoh, J. and Holdsworth, D.W., 2017. Reliable, non-destructive bulk volume and density determination of meteorites using medical X-ray micro computed tomography (microCT). CGU Annual Meeting, Vancouver, BC, May, 2017.

Warsame*, H.S., McCausland, P.J.A., White, C.E., Barr, S.M. and Dunning, G.R. 2017. Age and preliminary paleomagnetic assessment of the Silurian Mavillette gabbro, Meguma terrane, Nova Scotia, Canada. GAC-MAC Annual meeting, Kingston, ON, May 2017.

Thomson*, A.M., Tsujita, C.J., and McCausland, P.J.A. 2017. Paleoenvironmental implications of rugose coral growth ridges in the Middle Devonian Hungry Hollow Member, Michigan Basin. GAC-MAC Annual meeting, Kingston, ON, May 2017

Fernandes*, E.A., McCausland, P.J.A., Pilles, E. Osinski, G.R. 2017. Magnetic fabric study and the emplacement of sulfide deposits in the North Range offset dykes of the Sudbury Impact Structure, Ontario, Canada. GAC-MAC Annual meeting, Kingston, ON, May 2017.

Gunawardana*, H., McCausland, P.J.A., Good, D.J. and McBride, J. 2017. Use of Anisotropy of Magnetic Susceptibility (AMS) to analyze petrofabrics in Cu and PGE bearing gabbroic units of the Marathon deposit, Ontario. Institute on Lake Superior Geology meeting, Wawa, ON, May 2017.

McCausland, P.J.A., Tait, K.T., Nicklin, I. and Flemming, R.L. 2017. Regolith Processing on L Chondrite Bodies as Witnessed by NWA 869. Lunar and Planetary Science Conference XLVIII, Houston, TX. March, 2017, Abstract # 1826.

Uribe*, D.D., McCausland, P.J.A., Izawa, M.R.M., Flemming, R.L., Moser, D. and Barker, I. 2017. Structural and chemical microanalaysis of anomalous enstatite achondrites via electron backscatter diffraction (EBSD). Lunar and Planetary Science Conference XLVIII, Houston, TX. March, 2017, Abstract # 2537.

McCausland, P.J.A., Bramble*, M.S., Brown, P.G., Umoh, J.U., and Holdsworth, D.W. 2016. Many meteorites in one: Spatial scale and range of variation in bulk physical and lithological properties of the Tagish Lake C2 chondrite. GAC-MAC Annual meeting, Whitehorse, YK. June 2016.

Warsame*, H.S., McCausland, P.J.A. and Waldron, J.W. 2016. Reassessment of Port au Port Peninsula Paleomagnetism, with New Preliminary Results. GAC Newfoundland & Labrador Section Spring meeting, St. John’s, NL. February, 2016.

Gunawardana*, H., McCausland, P.J.A. and Murphy, J.B. 2016. Paleomagnetism of the Devonian McAras Brook Formation, Avalonia, revisited. Atlantic Geoscience Society 2016 Colloquium, Truro, NS. February, 2016.

3.8 Department of Earth and Environmental Sciences, University of Windsor

(Maria T. Cioppa)

Ongoing Research Projects

1) Environmental magnetism: Beach sediment and topsoil magnetism as a proxy for sedimentary and anthropogenic processes
2) Determining the nature of remagnetizations in the Williston Basin, Western Canada and in Southern Ontario
3) Paleomagnetic and rock magnetic studies of hydrocarbon source rocks in the Western Canada Sedimentary Basin
4) Magnetic properties of oil sands in drill core

Paleomagnetic and Rock Magnetic Laboratory:
http://www1.uwindsor.ca/people/mcioppa/7/facilities

(David T.A. Symons)

Principal Research Interests:

a) Paleomagnetic studies of well-dated rock units to examine the tectonic evolution of the North American Cordillera, especially in Yukon.
b) Paleomagnetic dating of ore deposits that are not amenable to radiometric age dating in order to study their ore genesis.

Recent Research Projects:

a) Paleomagnetic Dating of Ore Deposits

The age of mineralization is the most crucial information needed to understand the genesis of an ore deposit and therefore, how to explore for such a deposit. However, several important types of ore deposits of Pb, Zn, Cu, Ba, Fe, F, etc., are not readily dated by convential radiometric methods, either because they do not contain the necessary radioactive minerals or because these minerals are too fine-grained to be confidently separated. Paleomagnetic dating methods can often provide the necessary age information for such difficult deposits, providing suitably sensitive laboratory equipment is available. The University of Windsor Paleomagnetic Laboratory was bult specifically for ore deposit studies and has been the world leader in this research for the past quarter of a century. Many examples of such studies can be found in the publications list. Current projects include the F deposits in southern Spain and the Jinding-type Zn-Pb deposits in northwest China.

b) North American Tectonics

The use of paleomagnetic methods to study the tectonic evolution of the Canadian Cordillera and Laurentian Shield remains a major research focus in our laboratory. Recent studies have been done on the Yukon-Tanana terrane in Yukon and the Keweenawan terrane in northern Michigan.

Publications:

Symons, D.T.A., Kawasaki, K., Diehl, J.F., 2018. Magnetization age from paleomagnetism of the Copper Harbor red beds, northern Michigan, USA, and its Keweenawan geological consequences. Canadian Journal of Earth Sciences, in press, DOI 10.1139/cjes-2017-0094.

Zhao, Y., Xue, C., Symons, D.T.A., Zhao, X., Zhang, G., Yang, Y., Zu, B., 2018. Temporal variations in the mantle source beneath the Eastern Tianshan nickel belt and implications for Ni-Cu mineralization potential. Lithos 314-315: 597-616.

Yalikun, Y., Xue, C., Symons, D.T.A., 2018. Paleomagnetic age and tectonic constraints on the genesis of the giant Jinding Zn-Pb deposit, Yunnan, China. Mineralium Deposita 53: 245-259.

Yalikun, Y., Xue, C., Dai, Z., Chi, G., Fayek, M., Symons, D., 2018. Microbial structures and possible bacterial sulfide fossils in the giant JinDing Zn-Pb deposit, Yunnan, SW-China: Insights into the genesis of Zn-Pb sulfide mineralization. Ore Geology Reviews 92: 61-72.

Zhao, Y., Xue, C., Liu, S., Symons, D.T.A., Zhao, X., Yang, Y., Ke, J., 2017. Copper isotope fractionation during sulfide-magma differentiation in the Tulaergen magmatic Ni-Cu deposit, NW China. Lithos 286-287: 206-215.

Symons, D.T.A., Kawasaki, K., McCausland, P.J.A., Hart, C.J.R., 2017. Palaeopole for the 69 Ma Prospector Mountain stock: a critique of the Carmacks/"Baja BC" transport estimate for Yukon, Canada. Geophysical Journal International 208: 349-367. doi: 10.1093/gji/ggw398

Symons, D.T.A., Kawasaki, K., Tornos, F., Velasco, F., Rosales, I., 2017. Temporal constraints on genesis of the Caravia-Berbes fluorite deposits of Asturias, Spain, from paleomagnetism. Ore Geology Reviews 80: 754-766.

Symons, D.T.A., Tornos, F., Kawasaki, K., Velasco, F., Rosales, I., 2015. Genetic constraints from paleomagnetic dating for the Aliva zinc-lead deposits, Picos de Europa Unit, northern Spain. Mineralium Deposita 50: 953-966.

Symons, D.T.A., McCausland, P.J.A., Kawasaki, K., Hart, C.J.R., 2015. Post-Triassic para-autochthoneity of the Yukon-Tanana Terrane: Paleomagnetism of the Early Cretaceous Quiet Lake Batholith. Geophysical Journal International 203: 312-326. doi: 10.1093/gji/ggv296.

Zu, G., Xue, C., Zhao, Y., Qu, W., Li, C., Symons, D.T.A., Du, A., 2015. Late Cretaceous metallogeny in the Zhongdian area: Constraints from Re-Os dating of molybdenite and pyrrhotite from the Honshan Cu deposit, Yunnan, China. Ore Geology Reviews 64: 1-12.

3.9 Laboratory of Paleomagnetism and Petromagnetism - University of Alberta

(Vadim A. Kravchinsky)

During the reporting period my six graduate students, collaborators and I have been working in a broad area of paleo and rock-magnetism and their applications to solid earth, stratigraphic, tectonic and environmental studies. Recent contributions are described below. The Laboratory of Paleomagnetism and Petromagnetism website is: https://sites.ualberta.ca/~vadim/Lab.htm

(1) Calculation of the ancient longitudes of continents (with grad students L.Wu, B. Lysak, E. Kozmina):
A new method was developed to derive paleolongitude by geometrically parameterizing an apparent polar wander path (APWP). Using this method we re-evaluated the dispersion history of East Gondwana since 140 Ma. A Matlab based software was developed to implement the method. New absolute plate tectonic reconstructions were produced for the blocks surrounding the Mongol-Okhotsk Ocean from 250 Ma to the present day using the PMTec combined with seismic tomography data comprehensive analysis. We continue working on improving the paleomagnetic data base and APWPs in different regions.

(2) A link between giant magmatic events and the geomagnetic field (with grad students T. Anwar and collaborators A. Biggin and L. Hawkins (Liverpool), V. Pavlov (Moscow)):
It was demonstrated that the paleointensity of the geomagnetic field during the giant magmatic events at the Permo-Triassic boundary and at the end of Devonian was a few times lower than that of the present day. Such weak field values, along with moderate to high reversal frequencies and a potentially significant multipolar component, suggest that convection in the Earth's core was more forceful than today.

(3) Rock-magnetism, magnetostratigraphy and cyclostratigraphy applied to paleoclimate evaluation and geomagnetic field behavior (with grad students T. Anwar, J. Chen, R. Borowiecki, and collaborators R. Zhang (Xi'an), T. Evans and B. Jensen (Edmonton)):
Alaskan, Siberian, and Chinese loess and red clay deposits along with deep lake sediments are the best continental climate recorders for thousand and million year time scales, providing the highest resolution of geomagnetic and climatic events in the Cenozoic Era. Our new results from such deposits enabled us to evaluate both short and long-term climatic variations and to speculate about mechanisms that led to such climate changes. We firmly demonstrated that the use of cyclostratigraphy in addition to magnetostratigraphy provide the best age model and therefore climate dynamics evaluation.

Our analysis of the geomagnetic reversal frequency, oxygen isotope record, and tectonic plate subduction rate, which are indicators of changes in the heat flux at the core mantle boundary, climate fluctuation, and plate tectonic activity, showed that all these changes indicate similar rhythms on a million year timescale in the Cenozoic Era.

The unique continuity of the drilling cores from the deepest lake on Earth, Lake Baikal, enabled us to reconstruct the geomagnetic polarity chrons and a number of shorter geomagnetic events that occurred in the last 8.4 Myr.

(Ted Evans)
(1) Magnetoclimatology of Alaskan Loess:
Geomagnetic excursions have been identified: the Kamikatsura Excursion at Gold Hill and the the post-Blake (=Skálamælifell) Excursion at Halfway House (Jensen et al., 2016). These provide robust chronological control points that are essential for a proper assessment of regional palaeoclimatic evolution. We are currently attempting to refine the chronology by matching magnetic susceptibility signals to Heinrich Events, and by comparing relative palaeointensity fluctuations to global summaries (SINT, PISO). Magnetic susceptibility at these Alaskan sites is mostly driven by wind vigour, but subtle variations are found. These are being investigated by further mineral-magnetic experiments (IRM, ARM, FD, FORC).

(2) Geocentric Axial Dipole (GAD) hypothesis:
The probability distribution functions of field models consisting of an underlying GAD on which is superimposed modest zonal quadrupole and octupole components have been calculated and compared to an updated version of the global palaeointensity database (PINT). We find that a GAD with a 10% octupole component provides a good fit to the Phanerozoic and Precambrian data (Veikkolainen et al., 2017).

(3) Geomagnetic Polarity Reversals:
An extremely rapid Brunhes-Matuyama transition (13±6 years) was recently reported by Sagnotti et al. (Geophysical Journal International, 204, 798-212, 2016). We have studied parallel samples that question their conclusion. Detailed mineral magnetic experiments suggest that remagnetization is common in the sediments involved (Evans and Muxworthy, 2018a). We are currently carrying out dynamo simulations to explore in detail the spatio-temporal properties of reversals.

(4) Precambrian Plate Tectonics:
Vaalbara is the name given to a proposed configuration of continental blocks—the Kaapvaal craton (southern Africa) and the Pilbara craton (north-western Australia)—thought to be the Earth's oldest supercontinent. Our updated analysis shows that the existence of a single continent from ~2.9 to ~2.7 Ga is inconsistent with the available palaeomagnetic data (Evans na Muxworthy, 2018b). However, permissible configurations allow an ocean to open up between Kaapvaal and Pilbara after ~2.9 Ga, and then close again some 200 Ma later—the very first Wilson Cycle?

(5) Archaeomagnetism:
Secular variation coverage in Iberia has been extended by archaeomagnetic results from four Roman pottery kilns in Portugal. All the samples behaved in a very coherent manner during progressive alternating-field demagnetization and yielded high-precision mean directions for each site. The results lead to a more precise chronology than that provided by the known archaeological details (Evans and Correia, 2018).

University of Alberta - Laboratory of Paleomagnetism and Petromagnetism
Publications:

Hawkins L.M.A. , Anwar T., Shcherbakova V.V., Biggin A.J., Kravchinsky V.A., Shatsillo A.V., Pavlov V.E., 2019. An exceptionally weak Devonian geomagnetic field recorded by the Viluy Traps, Siberia. Earth and Planetary Science Letters 506, 134-145.

Anwar, T., Kravchinsky, V.A., Zhang, R., Koukhar, L.P., Yang, L., Yue, L., 2018. Holocene climatic evolution at the Chinese Loess Plateau: testing sensitivity to the global warming-cooling events, Journal of Asian Earth Sciences 166, 223-232.

Zhang., R., Kravchinsky, V.A., Anwar, T., Li, J., Jiao J., 2018. Comment on "Late Miocene-Pliocene Asian monsoon intensification linked to Antarctic ice-sheet growth" [Earth Planet. Sci. Lett. 42 (2016) 75-87]. Earth and Planetary Science Letters 503, 248-251.

Evans, M.E. and Muxworthy, A.R., 2018a. A re-appraisal of the proposed rapid Matuyama-Brunhes geomagnetic reversal in the Sulmona Basin, Italy, Geophysical Journal International, 218, 1744-1750.

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Evans, M.E. and Correia, A., 2018. Archaeomagnetism of four pottery kilns in central Portugal: Implications for secular variation and dating, Open Journal of Archaeometry, 4:7171.

Veikkolainen, T., Heimpel, M., Evans, M.E., Pesonen, L.J. and Korhonen, K., 2017. A paleointensity test of the geocentric axial dipole (GAD) hypothesis, Physics of the Earth and Planetary Interiors, 265, 54-61.

Anwar, T., Mumpy, A.J., Blanco, D., Kravchinsky, V.A., Catuneanu, O., 2017. Core Magnetostratigraphy: Chron 33r in the Southern Alberta Plains. Bulletin of Canadian Petroleum Geology 65 (4), 425-435.

Wu, L., Kravchinsky, V.A., Gu, Y.J., Potter, D.K., 2017. Absolute reconstruction of the closing of the Mongol-Okhotsk Ocean in the Mesozoic elucidates the genesis of the slab geometry underneath Eurasia. Journal of Geophysical Research

Kravchinsky, V.A., 2017. Magnetostratigraphy of the Lake Baikal sediments: A unique record of 8.4 Ma of continuous sedimentation in the continental environment. Global and Planetary Change 152, 209–226.

Wu, L., Kravchinsky, V.A., Potter, D.K., 2017. Apparent polar wander paths of the major Chinese blocks since the Late Paleozoic: Toward restoring the amalgamation history of east Eurasia. Earth-Science Reviews 171, 492–519.

Anwar, T., Hawkins, L., Kravchinsky, V.A., Biggin, A.J., Pavlov, V.E., 2016. Microwave paleointensities indicate a low paleomagnetic dipole moment at the Permo-Triassic boundary. Physics of the Earth and Planetary Interiors 260, 62–73

Jensen, B.J.L., Evans, M.E., Froese, D.G., Kravchinsky, V.A., 2016. 150,000 years of loess accumulation in central Alaska. Quaternary Science Reviews 135, 1–23.

Kravchinsky, V.A., 2015. Geomagnetism. Encyclopedia of Scientific Dating Methods, 298-301. Springer.

Wu, L., Kravchinsky, V.A., Potter, D.K., 2015. A new MATLAB toolbox for absolute plate motion reconstructions from paleomagnetism. Computers & Geosciences 82, 139–151.

Chen, J., Liu, X., Kravchinsky, V.A., Lv, B.; Chen, Q., 2015. Post-depositional forcing of magnetic susceptibility variations at Kurtak section, Siberia. Quaternary International.

Anwar, T., Kravchinsky, V.A., Zhang, R., 2015. Magneto- and cyclostratigraphy in the red clay sequence: New age model and paleoclimatic implication for the Eastern Chinese Loess Plateau. Journal of Geophysical Research.

Chen, J., Kravchinsky, V.A., Liu, X., 2015. The 13 million year Cenozoic pulse of the Earth. Earth and Planetary Science Letters 431, 256–263.

3.10 Department of Geography – University of Lethbridge

(René W. Barendregt)

My research is focused on paleoenvironments and climate change, in particular the glacial/interglacial sedimentary records in Canada which provide an archive of climate change as well as proxies of permafrost, snow, ice, and vegetation conditions. The latter inform important global feedback mechanisms that influence climate. Paleomagnetism, magnetostratigraphy, and rock magnetic properties serve as useful geophysical tools in correlation and dating of deposits, and provide a measure of sediment provenance and weathering histories. Field research is based at localities worldwide, throughout South America, North America, Europe and Africa.

Recent paleomagnetic and rock magnetic research includes:

1) Late Cenozoic paleoenvironments and climate change: a western hemisphere comparison of continental, cordilleran, and local montane and upland glacial/interglacial records (North and South America).

2) Late Cenozoic magnetostratigraphy and proxy records of climate change obtained from glacial/interglacial sequences on four continents (North and South America, Europe, and Africa).

3) Late Cenozoic magnetostratigraphy of gold and diamond-bearing gravels: reconstruction of river terrace chronosequences, paleoflow, and sediment provenance.

4) Time Averaged Paleo-secular variation of earth's magnetic field during the past 5.0 Ma obtained from basalts at 50° to 65° north and south latitude.

5) Paleosols and their parent materials provide a valuable record of past climate and vegetation conditions, and the age and extent of these deposits are likewise determined by magnetostratigraphy and rock magnetic characterization.

Publications:

Roberts, N.J., Barendregt, R.W. and Clague, J.J. 2018. Pliocene and Pleistocene chronostratigraphy of continental sediments underlying the Altiplano at La Paz, Bolivia: Quaternary Science Reviews, 189: 105-126. https://doi.org/10.1016/j.quascirev.2018.03.008

Westgate, J.A., Gabriel, G.W., Halls, H.C., Bray, C.J., Barendregt, R.W., Pearce, N.J.G., Sarna-Wojcicki, A.M., Gorton, M.P., Kelley, R.E. and Schultz-Fellenz, E. 2018. Quaternary tephra from the Valles caldera in the volcanic field of the Jemez Mountains of New Mexico identified in Western Canada. Quaternary Research, 86

Andriashek, L. and Barendregt, R.W. 2017. Evidence for Early Pleistocene Glaciation from Borecore Stratigraphy in North-Central Alberta: Canadian Journal of Earth Sciences, 54 (2): 445-465. (doi:10.1139/cjes-2016-0175)

Roberts, N.J., Barendregt, R.W. and Clague, J.J. 2017. Multiple tropical Andean glaciations during a period of late Pliocene warmth: Nature, Scientific Reports, 7:41878, doi:10.1038/srep41878

Hanson, M.A., Enkin, R.J., Barendregt, R.W. and Clague, J.J. 2015. Provenance and Deposition of Glacial Lake Missoula Lacustrine and Flood Sediments Determined from Rock Magnetic Properties: Quaternary Research, 83: 166-177.

3.11 Paleomagnetism and Petrophysics Laboratory - Geological Survey of Canada (Pacific)

(Randy J. Enkin)

The Geological Survey of Canada – Paleomagnetism and Petrophysics Laboratory has recently undergone significant renovations to upgrade sample preparation and analysis of rock magnetic, paleomagnetic and petrophysical properties. Over the last four years the Laboratory has focused on petrophysical applications to mineral exploration and the compilation of a Canadian Rock Physical Property Database. https://doi.org/10.4095/313389

A significant review of these methods and data took place in a one-day workshop at the Exploration '17, Decennial Mining Exploration Conference, held in Toronto, October 2017: "Improving Exploration with Petrophysics: The Application of Magnetic Remanence and Other Rock Physical Properties to Geophysical Targeting". Randy Enkin and Bill Morris were on the organizing committee. The workshop reviewed the characteristics of remanent magnetization in rocks, and presented the tools to detect and recover remanent magnetization information from interpretation of magnetic field data.

Publications:

Enkin, R.J., "The Canadian Rock Physical Property Database – First Public Release"; Geological Survey of Canada, Open File 8460, 126 p. https://doi.org/10.4095, 2018

Greene, H.G., Barrie, J.V., Brothers, D.S., Conrad, J.E., Conway, K., East, A.E., Enkin, R.J., Maier, K.L., Nishenko, S.P., Walton, M.A.L., and Rohr, K.M.M., "Slope failure and mass transport processes along the Queen Charlotte Fault Zone, western British Columbia", Geological Society, London, Special Publications, 477, 1-22, doi.org/10.1144/SP477.31, 2018.

Perrouty, S., Linnen, R.L., Lesher, C.M., Olivo, G.R., Piercey, S.J., Gaillard, N., Clark, J.R., Enkin, R.J., "Expanding the size of multi-parameter metasomatic footprints in gold exploration: utilization of mafic dykes in the Canadian Malartic district, Québec, Canada", Mineralum Deposita, 1-26, doi.org/10.1007/s00126-018-0829-x, 2018

Stacey, C.D., Lintern, D.G., and Enkin, R.J., “Multifaceted re-analysis of the enigmatic Kitimat slide complex, Canada”, Sedimentary Geology, 369, 46-59, 10.1016/j.sedgeo.2018.01.006, 2018

Bérubé, C.L., Olivo, G., Chouteau, M., Perrouty, S., Shamsipour, P., Enkin, R.J., Morris, W.A., Feltrin, L., Thiémonge, R., “Predicting rock type and detecting hydrothermal alteration using machine learning and petrophysical properties of the Canadian Malartic ore and host rocks, Pontiac Subprovince, Québec, Canada”, Ore Geology Reviews, 96, 130-145, doi.org/10.1016/j.oregeorev.2018.04.011, 2018

Stacey, C.D., Hill, Talling, Enkin, R., Hughes Clark, “How turbidity current frequency and character varies down a fjord-delta system: Combining direct monitoring, deposits and seismic data”, Sedimentology, doi.org/10.1111/sed.12488, 2018

Bérubé, C.L., Chouteau, M., Shamsipour, P., Olivo, G.R., Enkin, R.J., "Bayesian inference of spectral induced polarization parameters for laboratory complex resistivity measurements of rocks and soils", Computers and Geosciences, 105, 51-64, DOI10.1016/j.cageo.2017.05.001, 2017.

Schetselaar, E., Bellefleur, G., Craven, J., Roots, E., Cheraghi, S., Shamsipour, P., Caté, A., Mercier-Langevin, P., El Goumi, N., Enkin, R., Salisbury, M., “Geologically-driven 3D stochastic modelling of physical rock properties in support of interpreting the seismic response of the Lalor volcanogenic massive sulphide deposit, Snow Lake, Manitoba, Canada”, Geological Society of London Special Publication 453: “Advances In The Characterization Of Ore-Forming Systems From Geological/Geochemical/Geophysical Data”, P. Sorjonen Ward and K. Gessner, ed.s, DOI: 10.1144/SP453.5, 23pp, 2017.

Enkin, R.J., Corriveau, L., and Hayward, N., “Metasomatic alteration control of petrophysical properties in the Great Bear Magmatic Zone (Northwest Territories, Canada)”, Economic Geology, 111, 2073–2085, 2016

Hayward, N., Corriveau, L., Craven, J.A., and Enkin, R.J., “Geophysical signature of the Au-Co-Bi-Cu NICO deposit and its iron oxide alkali alteration system, Northwest Territories, Canada”, Economic Geology, Economic Geology, v. 111, i. 8, p. 2087-2109, 2016

Bringué,, M., Pospelova, V., Calvert, S.E., Enkin, R.J., Ivanochko, T., and Lacourse, T., “High resolution dinoflagellate cyst record of environmental change in Effingham Inlet (British Columbia, Canada) over the last millennium”, Palaeogeography, Palaeoclimatology, Palaeoecology 441, 787-810, 2016, https://doi.org/10.1016/j.palaeo.2015.10.026

Hamilton, T.S., Enkin, R.J., Riedel, M., Rogers, G.C. and Pohlman, J., “Paleoseismicity of the Cascadia Accretionary Wedge off of Western Canada: Slipstream; an Early Holocene Slump and Turbidite Record from the Frontal Ridge”, Canadian Journal of Earth Sciences, 52(6): 405-430, 10.1139/cjes-2014-0131, 2015.

4 Space Physics

Compiled by David R. Themens, University of New Brunswick (David.Themens@unb.ca)

This report is divided into to main categories: Atmospheric Studies, including the study of the Stratosphere, Mesosphere, and Thermosphere; and Space Physics, which includes the study of the Ionosphere, Magnetosphere, and Solar Wind Interactions.

4.1 Atmospheric Studies

We begin first with a brief summary of the atmospheric research programs that have been conducted within Canada over the past quadrennial and subsequent lists of relevant publications resulting from these programs.

4.1.1 Centre for Research in Earth and Space Science, York University

During this period development of the Canadian Ionosphere and Atmosphere model (C-IAM) was completed. The C-IAM is a first principles global 3D model extending from the surface to the plasmasphere, which incorporates all known major physical and chemical processes of importance within its domain. The model is able to calculate in a self-consistent manner the atmospheric composition (neutral species, ions and electrons), temperature, motion (neutral wind, plasma drift) and the electric field of both magnetospheric and dynamo origin. As well the group has obtained access to the USA WACCM-X model for some comparison with data from the Wind Imaging Interferometer (WINDII). The group also developed a processing procedure to extract atomic oxygen concentrations from the WINDII O+ emission and compared it with that from NRLMSISE-00 and C-IAM models and with GUVI observations. The response of the upper mesosphere/lower thermosphere region to the dynamic effects of major sudden stratospheric warming (SSW) was examined employing temperature, wind and the residual circulation, as well as trace gases (NOX, and CO) from the extended Canadian Middle Atmosphere Model (Extended-CMAM). The Midnight Temperature Maximum (MTM) is a large-scale neutral temperature anomaly with a wide-ranging effect on the nighttime thermospheric dynamics at equatorial and low latitudes. An investigation of the extent of the MTM to northern and southern midlatitudes (20ºN – 40ºN) and (20ºS – 40ºS) was carried out employing multi-year observations of O(1D) nightglow volume emission rates, Doppler temperatures, and neutral winds over the altitude range of 190–300 km by WINDII. Also with WINDII an explanation of “bright nights” was found, where on otherwise dark nights the surroundings were visible, noted since Roman times. It was proposed that the superposition of the peaks of the different zonal waves, 1 to 4, was responsible. Ensemble based data assimilation techniques including ensemble Kalman filter and ensemble-variational hybrid method were applied to improve tropospheric analysis and forecast. The impact of dust aerosols on tropical tropospheric weather were investigated using the data assimilation and numerical modeling system, in which conventional in-situ observations, and satellite observations were assimilated. In 2018, the atomic oxygen depletions mentioned above were investigated at higher latitudes and it was found that these occurred at the same longitudes as strong wind reversals, eastward to westward with the westward as large as 600 m s-1. This reversal was described as a “wind wall”. A miniaturized spatial heterodyne spectrometer was designed and built for the measurement of O2 rotational temperatures in the upper mesosphere; it is now awaiting launch. Marianna Shepherd organized SCOSTEP's 14th Quadrennial Solar-Terrestrial Physics Symposium at York University.

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4.1.2 Department of Physics, University of New Brunswick

UNB's Dr. William Ward operates a suite of instruments providing observations of the mesopause region and the middle thermosphere is sited at Eureka, Nunavut, Canada in the high Arctic Polar Environment Atmospheric Research Laboratory (PEARL: 80° N, 86° W, since 2007/2008). Another set of instruments is sited at Resolute Bay, Nunavut (75°N, 95°W, since 2014/2015). These instruments provide winds, temperatures and airglow irradiance in the mesopause regions and in the thermosphere. The instrumentation includes a Michelson interferometer, Fabry Perot interferometer, Spectral Airglow Temperature, and an all-sky airglow imager. Dr. Ward's research focuses on the improvement of these various interferometric instruments, as well as on wave coupling within the mesosphere/thermosphere/ionosphere system in collaboration with the group developing C-IAM at York University.

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4.1.3 Department of Physics and Astronomy, University of Western Ontario

Western's Dr. Wayne Hocking operates atmospheric radars to study the motion and turbulence of the mesosphere and lower thermosphere. These instruments include two wind-profilers and four meteor radars. These instruments all measure atmospheric wind motions, although in different ways. The wind-profiler radars utilize radio-wave scatter from inhomogeneities in the clear air which are generated by turbulence and other small-scale phemomena, whilst the meteor radars use scatter from meteor trails at 80 to 100 km altitude. The doppler shift of the back-scattered radio waves are used to calculate the velocities of the scattering entities and hence the velocity of the atmospheric winds at the height of scatter.

Two of Dr. Hocking's radars are located near London, Ontario (close to the University of Western Ontario) and two are at Resolute bay in Nunavut (Canada), with each site possessing a wind-profiler radar and a meteor radar. In addition, they operate meteor radars at Yellowknife in the North-West Territories of Canada, and at Socorro in New Mexico (USA). The Socorro radar is in fact provided by Mardoc Inc, through a leasing arrangement with UWO.

Related Publications:

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4.1.4 Department of Physics, University of Toronto

Like the groups at UNB and Dalhousie, the University of Toronto group is heavily involved with the PEARL observatory, but with main focus on the stratosphere. Dr. Strong is the lead scientist of four instruments at PEARL: a Bruker Fourier transform infrared (FTIR) spectrometer, two UV-visible grating spectrometers, and an Extended-range Atmospheric Emitted Radiance Interferometer. From 2010-2016, Dr. Strong was the Director for the NSERC CREATE Training Program in Arctic Atmospheric Science, which was closely affiliated with PEARL activities. Over the last several years, the group has documented the transport of biomass burning products into the High Arctic, including the first long-term time series of ammonia in the high Arctic, measured greenhouse gases, investigated bromine explosion events and their impact on tropospheric ozone, and contributed to long-term trend studies. In addition to their involvement in PEARL, Dr. Strong's group is involved in the operation of the Toronto Atmospheric Observatory (TAO), which includes a Bomem DA8 high-resolution FTIR spectrometer for long-term measurements of stratospheric and tropospheric trace gases, urban pollution and stratospheric chemistry studies, and satellite validation.

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4.2 Space Plasma: Ionosphere-Magnetosphere

This section is structured to first summarize Canadian involvement in space-born instrumentation and associated studies before then discussing Canadian ground-based infrastructure achievements and outcomes.

4.2.1 CASSIOPE ePOP

In late 2013, the ePOP payload onboard the CASSIOPE satellite was launched with the following objectives: 1) to quantify the microscale characteristics of plasma outflow and related micro- and meso-scale plasma processes in the polar ionosphere; 2) to explore the occurrence morphology of neutral escape in the upper atmosphere; 3) to study the effects of auroral currents on plasma outflow and those of plasma microstructures on radio propagation.

Table 1 ePOP payload instrument descriptions and Principle Investigator (PI) list.

Instrument	Description	PI	Scientific Output
CER	Coherent EM Radio Tomography	Bernhardt	Electron content
FAI	Fast Auroral Imager	**Cogger**	Infrared and visible images
GAP	GPS Attitude and Profiling Experiment	**Langley**	Spacecraft position and attitude
IRM	Imaging and Rapid-Scanning Ion Mass Spectrometer	**Yau**	Low energy ion detection
MGF	Fluxgate Magnetometer	**Wallis**	3-D magnetic field and currents
NMS	Neutral Mass Spectrometer	Hayakawa	0.1-2km/s neutral particles
RRI	Radio Receiver Instrument	**James**	Radio wave propagation
SEI	Suprathermal Electron Imager	**Knudsen**	Low energy electron detection

The e-POP payload consists of eight scientific instruments, including imaging plasma and neutral particle sensors, magnetometers, radio wave receivers, dual-frequency GPS receivers, CCD cameras, and a beacon transmitter. The imaging plasma sensors (SEI and IRM) measure particle distributions and the magnetometers (MGF) measure field aligned currents on the time scale of 10-ms and spatial scale of ~100 m. The neutral mass and velocity spectrometer (NMS) measures the density and velocity of major atmospheric species. The CCD cameras (FAI) perform auroral imaging on the time scale of one second. The radio wave and GPS receivers (RRI and GAP) perform near real-time imaging studies of the ionosphere, in conjunction with ground-based radars, as does the beacon transmitter (CER), in conjunction with ground receiving stations.

Table 2 Publications using ePOP instruments since 2015.

Subject	Authors and Title	Journal
e-POP	Yau A.W., Z. Ali, C. Alonso, C. Casgrain, G.A. Enno, B. Entus, M. Grigorian, J. Hemingway, A. Howarth, R.H. Hum, H.G. James, P. Langlois, M. Senez, A. White	Acta Astronautica (2015)
	The Canadian CASSIOPE Small Satellite Mission: The Enhanced Polar Outflow Probe and Cascade Technology Demonstration Payloads	DOI: 10.1016/j.actaastro.2015.01.016
e-POP	Yau A.W., and H.G. James	Space Sci. Rev. (2015)
	CASSIOPE Enhanced Polar Outflow Probe (e-POP) Mission Overview	DOI: 10.1007/s11214-015-0135-1
FAI	Lui A.T.Y., L.L. Cogger, A. Howarth, A.W. Yau	Geophys. Res. Lett., (2015) 42
	First Satellite Imaging of Auroral Pulsations by the Fast Auroral Imager on e-POP	DOI: 10.1002/2015GL065331
GAP	Shume E.B., A. Komjathy, R.B. Langley, O. Verkhoglyadova, M.D. Butala, and A.J. Manucci	Geophys. Res. Lett. (2015)
	Intermediate scale plasma irregularities in the polar ionosphere inferred from GPS radio occultation	DOI: 10.1002/2014GL062558
GAP	Shume E.B., P. Vergados, A. Komjathy, R. B. Langley, T. Durgonics	Radio Science (2017)
	Electron number density profiles derived from radio occultation on the CASSIOPE spacecraft	DOI: 10.1002/2017RS006321
GAP	Watson C., R.B. Langley, D.R. Themens, A.W. Yau, A.D. Howarth, P.T. Jayachandran	Radio Science (2018)
	Enhanced Polar Outflow Probe ionospheric radio occultation measurements at high latitudes: Receiver bias estimation and comparison with ground-based observations	DOI: 10.1002/2017RS006453
IRM	Yau A.W., A. Howarth, A. White, G. Enno, P. Amerl	Space Sci. Rev. (2015)
	Imaging and Rapid-Scanning Ion Mass Spectrometer (IRM) for the CASSIOPE e-POP Mission	DOI: 10.1007/s11214-015-0149-8
IRM	Marchand R., S. Hussain	IEEE Transactions on Plasma Science (2015)
	Aberrations in Particle Distribution Functions Near e-POP Particle Sensors	DOI: 10.1109/TPS.2015.2428715
IRM	Yau A.W., A. Howarth	J. Geophys. Res. Space Physics (2016)
	Imaging thermal plasma mass and velocity analyzer	DOI: 10.1002/2016JA022699

IRM	Durgonics T., A. Komjathy, O. Verkhoglyadova, E.B. Shume, H.-H. Benzon., A.J. Mannucci, M.D. Butala, P. Høeg, R.B. Langley Multiinstrument observations of a geomagnetic storm and its effects on the Arctic ionosphere: A case study of the 19 February 2014 storm	Radio Science (2017) DOI: 10.1002/2016RS006106
MGF	Miles D.M., I.R. Mann, I.P. Pakhotin, J.K. Burchill, A.D. Howarth, D.J. Knudsen, R.L. Lysak, D.D. Wallis, L.L. Cogger, and A.W. Yau Alfvénic Dynamics and Fine Structuring of Discrete Auroral Arcs: Swarm and e-POP Observations	Geophys. Res. Lett. (2018) DOI: 10.1002/2017GL076051
RRI	James H.G., E.P. King, A. White, and R.H. Hum, W.H.H.L. Lunscher, and C.L. Siefring The e-POP Radio Receiver Instrument on CASSIOPE	Space Sci. Rev. (2015) DOI: 10.1007/s11214-014-0130-y
RRI	Burrell A.G., S.E. Milan, G.W. Perry, T.K. Yeoman, M. Lester Automatically determining the origin direction and propagation mode of high-frequency radar backscatter	Radio Science (2015) DOI: 10.1002/2015RS005808
RRI	Perry G. W., H. G. James, R. G. Gillies, A. Howarth, G. C. Hussey, K. A. McWilliams, A. White, and A. W. Yau First results of HF radio science with e-POP RRI and SuperDARN	Radio Science (2016) DOI: 10.1002/2016RS006142
RRI	Burrell A.G. e-POP RRI provides new opportunities for space-based, high-frequency radio science experiments	Radio Science (2017) DOI: 10.1002/2017RS006257
RRI	James H. G., V. L. Frolov, E. S. Andreeva, A. M. Padokhin, and C.L. Siefring Sura heating facility transmissions to the CASSIOPE/e-POP satellite	Radio Science (2017) DOI: 10.1002/2016RS006190
RRI	Leyser T. B., H.G. James, B. Gustavsson, and M. T. Rietveld Evidence of L-mode electromagnetic wave pumping of ionospheric plasma near geomagnetic zenith	Annales Geophysicae (2018) DOI: 10.5194/angeo-36-243-2018
RRI	Danskin D.W.,G. C. Hussey,R. G. Gillies, H.G. James, D. T. Fairbairn, A. W. Yau Polarization Characteristics Inferred From the Radio Receiver Instrument on the Enhanced Polar Outflow Probe	J. Geophys. Res. Space Physics (2018) DOI: 10.1002/2017JA024731
RRI	Burrell A. B., G. W. Perry, T. K. Yeoman, S. E. Milan, R. Stoneback Solar Influences on the Return Direction of High-Frequency Radar Backscatter	Radio Science (2018) DOI: 10.1002/2017rs006512

RRI	James H.G. Propagation Directions of High-Frequency Waves in the Ionosphere	Radio Science (2018) DOI: 10.1002/2017RS006474
SEI	Knudsen D.J., J.K. Burchill, T.G. Cameron, G.A. Enno, A. Howarth, and A.W. Yau The CASSIOPE/e-POP Suprathermal Electron Imager (SEI)	Space Sci. Rev. (2015) DOI: 10.1007/s11214-015-0151-1
SEI	Cameron T., and D. Knudsen Inverse electron energy dispersion from moving auroral forms	J. Geophys. Res. Space Physics (2016) DOI:10.1002/2016JA023045
SEI	Shen Y., D. J. Knudsen, J. K. Burchill, A. Howarth, A. W. Yau, R. J. Redmon, D. M. Miles, R. H. Varney, and M. J. Nicolls Strong ambipolar-driven ion upflow within the cleft ion fountain during low geomagnetic activity	J. Geophys. Res. Space Physics (2016) DOI:10.1002/2016JA022532

Since launch, the ePOP payload has served an exceptional role in fostering international collaboration with the Canadian space physics community. The RRI instrument, in particular has seen broad international application in studying high frequency EM propagation within plasma in conjunction with ground-based instruments, such as the Sura heater facility, SuperDARN, and ground-based ionosondes. Canada's extensive networks of ground-based instruments served to strongly complement ePOP satellite-born observations. In recognition of the uniqueness and high quality of the ePOP payload, the satellite has been taken on by the European Space Agency to extend its operational life and is now considered as the fourth Swarm satellite, Swarm E.

4.2.2 Swarm

In addition to an EFI being deployed as part of the ePOP payload, EFI instruments were also included on the Swarm satellites. The Swarm mission was designed to make the best-ever measurements of the Earth's low-frequency electromagnetic field environment. Two of the Swarm satellites orbit at an altitude of approximately 460 km; the third is at 510 km. Each satellite carries identical instrumentation including an EFI comprising two Thermal Ion Imagers (TIIs) and two Langmuir probes (LPs), all provided by a consortium that includes the University of Calgary, the Swedish Institute for Space Physics (IRF), and COM DEV International.

Canadian involvement in Swarm has included the identification of widespread occurrence of Alfven waves in high-latitude M-I coupling [Miles et al., 2018; Pakhotin et al., 2018], clarification of a newly-identified high-intensity flow feature at the R1/R2 FAC boundary [Archer and Knudsen, 2018; Aikio et al., 2018], discovery of intense ionospheric heating by plasma waves at unprecedentedly low altitudes [Shen et al., 2018], identification of hundreds of examples of "FLR arcs" with in-situ field measurements in one case [Gillies et al., 2018], report of new type of "non-aurora" (STEVE) [MacDonald et al., 2018], and ground-based calibration and validation of Swarm plasma density measurements [Lomidze et al., 2018].

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4.2.3 GO Canada

One of the greatest contributions from Canadian researchers over the past quadrennial has been their continued deployment and operation of ground-based infrastructure, namely the GO Canada instrument networks. These networks are summarized in Table 3.

Table 3 GO Canada instrument network descriptions.

GO Canada Instrument & Data Projects

Acronym	Project	Subproject	PI	Institution
ABOVE	Array for Broadband Observations of VLF/ELF Emissions	[none]	**Christopher Cully**	University of Calgary
AGO	Auroral Geospace Observatory	AGO	**Eric Donovan**	University of Calgary
		REGO		
AIM	Arctic Ionosphere Monitoring	DIA	**P.T.**	University of

		EGPS	**Jayachandran**	New Brunswick
AUTUMNX	Athabasca University THEMIS UCLA Magnetometer Network Extension	[none]	**Martin Connors**	University of Athabasca
CARISMA	Canadian Array for Realtime Investigations of Magnetic Activity	MLMA	**Ian Mann**	University of Alberta
		HLMA		
CARISMA	Canadian Array for Realtime Investigations of Magnetic Activity	ICM	**David Milling**	University of Alberta
		NGEN		
DNT	Dynamics of the Neutral Thermosphere	[none]	**William Ward**	University of New Brunswick
H+Storm	Observatory for protons during storm-time	[none]	**Brian Jackel**	University of Calgary
RIO	Riometer Network	RIO	**Emma Spanswick**	University of Calgary
		IRIS		
SuperDARN	Super Dual Auroral Radar Network	SAS	**Kathryn McWilliams**	University of Saskatchewan
		PGR		
		INV		

These extensive networks of overlapping and complementary observations are unique to Canada and position the community to engage in frontier research that wholly complements space-born assets. The following sections outline the instrumentation of each network and discuss the outcomes of these programs over the past quadrennial.

4.2.3.1 ABOVE

ABOVE is an array of eight instruments for observing broadband VLF/ELF emissions. The instruments are sensitive to electromagnetic waves in the frequency range from 100 Hz to 75 kHz, covering the Extremely Low Frequency (ELF) and Very Low Frequency (VLF) bands of the radio spectrum.

ABOVE^2 is a balloon campaign that augments the ground-based array of ABOVE receivers to provide high-altitude measurements of X-rays and ELF/VLF radio waves related to electron precipitation from Earth's radiation belts. The campaign consists of 3 hand-launched balloons, each carrying an X-ray scintillator and a VLF radio receiver used to study electron microbursts.

4.2.3.2 AGO/REGO

The University of Calgary's Auroral Imaging Group (AIG) operates a network of six all-sky imagers (AGO) and eight red line auroral imagers (REGO).

Related Publications:

Gillies, D. M., **Knudsen**, D., **Rankin**, R., Milan, S., & **Donovan**, E. (2018). A statistical survey of the 630.0-nm optical signature of periodic auroral arcs resulting from magnetospheric field line resonances. Geophysical Research Letters, 45, 4648–4655. https://doi.org/10.1029/2018GL077491

Mushini, S. C., **Skone**, S., **Spanswick**, E., **Donovan**, E., & Najmafshar, M. (2018), Proxy index derived from All Sky Imagers for space weather impact on GPS, Space Weather

Gillies, D. Megan, D. Knudsen, E. Donovan, B. Jackel, R. Gillies, and E. Spanswick, Identifying the 630 nm auroral arc emission height: A comparison of the triangulation, FAC profile, and electron density methods, *J. Geophys. Res.*, 122, 8181–8197, 2017.

Liang, J., E. **Donovan**, B. **Jackel**, E. **Spanswick**, and M. **Gillies** (2016), On the 630 nm red-line pulsating aurora: Red-line Emission Geospace Observatory observations and model simulations, J. Geophys. Res. Space Physics, 121, 7988–8012, doi:10.1002/2016JA022901.

4.2.3.3 AUTOMNX

Athabasca University's program of investigation in space physics and astronomy continues to advance. The Athabasca University Geo Space Observatory, opened in a rural location in 2012, operates a wide range of auroral instrumentation, while the older site near the town has a reduced complement and mainly supports operation of a robotic telescope. Ongoing studies of proton aurora have been enhanced by the Arase satellite of our Japanese collaborators. The new FESO scanning photometer, developed in partnership with the University of Calgary, is the most sensitive detector of proton aurora in the world. The scattered magnetometers of the AUTUMN network in western Canada are supplemented by the carefully laid out meridian chain and subauroral sites of AUTUMNX in Québec, greatly increasing magnetometer coverage in eastern North American and near the Hydro-Québec electric grid. As we move from developing instrumental capability into analysis, techniques of magnetic inversion play a large role. Studies of asteroid orbits also continue, with the discovery of a "retrograde Trojan" orbit having been featured in Nature.

Over the past year, their analysis of magnetic data from Québec, complemented by grid monitoring data, has revealed a new class of magnetic disturbance, which we refer to as Large Impulsive Magnetic Events (LIME). These cause impulsive geomagnetic induced currents in the grid, and are accompanied by unusual streamer auroras, all developing on time scales of only minutes. Years of work on proton auroras this year saw large advances driven by Japanese colleagues, with relationship of very rapid pulsations in auroral light to waves detected in conjugate space locations by the Arase satellite.

Related Publications:

Mitsunori Ozaki, Yoshizumi Miyoshi, Kazuo Shiokawa, Keisuke Hosokawa, Shin-ichiro Oyama, Ryuho Kataoka, Yusuke Ebihara, Yasunobu Ogawa, Yoshiya Kasahara, Satoshi Yagitani, Hirotsugu Kojima, Yasumasa Kasaba, Atsushi Kumamoto, Fuminori Tsuchiya, Shoya Matsuda, Yuto Katoh, Mitsuru Hikishima, Satoshi Kurita, Yuichi Otsuka, Robert Moore, Yoshimasa Tanaka, Masahito Nose, Tsutomu Nagatsuma, Nozomu Nishitani, Akira Kadokura, Martin Connors, Takumi Inoue, Ayako Matsuoka, Iku Shinohara. Visualization of rapid electron precipitation via chorus element wave–particle interactions. Nature Communications, in press

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4.2.3.4 CARISMA

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4.2.3.5 E-CHAIN

The University of New Brunswick's Expanded-Canadian High Arctic Ionospheric Network (E-CHAIN) provides near-realtime high-rate GNSS measurements of phase and amplitude at 25 locations within the Canadian arctic. Eight of these stations are collocated with Canadian Advanced Digital Ionosondes, which provide drift at 30 second resolution and ionograms every 1-to-5 minutes, depending on site. Research highlights over the quadrennial include: 1) pioneering work in identifying the statistical and physical behaviour of GNSS scintillation at high latitudes [Prikryl et al., 2015a,b,c,d; Mezaoui et al., 2015; Wang et al., 2016; Prikryl et al., 2016; Mezaoui et al., 2017; Jayachandran et al., 2017; McCaffrey et al., 2017a,b; Mushini et al., 2018; Wang et al., 2018]; 2) the development of the Empirical Canadian High Arctic Ionospheric Model (E-CHAIM) high latitude electron density model, which acts as a replacement to the use of the International Reference Ionosphere (IRI) at high latitudes [Themens et al., 2016; Athieno et al., 2017; Themens et al., 2017a,b; Themens et al. 2018]; 3) case studies of patch and polar cap arc behaviour and dynamics [Hosokawa et al., 2015; Jayachandran et al., 2015; Durgonics, 2017; Zhang et al., 2017; Ma et al., 2018]; 4) the development of techniques to calibrate ground- and space-based GNSS measurements of Total Electron Content (TEC) [Themens et al., 2015; Prasad et al., 2016; McCaffrey et al., 2017; Watson et al., 2018]; 5) examining the behaviour of pulsations and ionospheric variations at high latitudes using GNSS measurements [Watson et al., 2015; Watson et al., 2016a,b; McCaffrey and Jayachandran, 2017]; and 6) assessing high frequency (HF) communication behaviour and availability at high latitudes [Athieno et al., 2015; Athieno and Jayachandran, 2016]

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4.2.3.6 H+Storm

The University of Calgary's Auroral Imaging Group (AIG) operates an array of Meridian Scanning Photometers (MSPs). The H+Storm project consists of two major types of MSPs: a filter-wheel MSP providing data across 4 individual wavelength (557.7nm green, 407.9nm blue, 630.0mm red, and 486.1nm H-Beta), and an 486.1nm H-Beta-specific system called FESO (Forty Eight Sixty One).

Related Publications:

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4.2.3.7 RIO

The University of Calgary's RIO project is a network of 14 traditional riometers and ten imaging riometers (IRIS) complementing NRCan's riometer network and overlapping GNSS and all sky imager instrument coverage.

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4.2.3.8 SuperDARN

The Canadian components of the SuperDARN network are operated by the University of Saskatoon in Clyde River, Rankin Inlet, Inuvik, Saskatoon, and Prince George. The SuperDARN radars operate in the HF band between 8.0 MHz (37m) and 22.0 MHz (14m). In the standard operating mode each radar scans through 16 beams of azimuthal separation of ~3.24°, with a scan taking 1 min to complete (~3 seconds integration per beam). Each beam is divided into 75 (or 100) range gates each 45 km in distance, and so in each full scan the radars each cover 52° in azimuth and over 3000 km in range; an area encompassing the order of 1 millon square km. The radars measure the Doppler velocity of plasma density irregularities in the ionosphere. Over the past quadrennial, SuperDARN Canada has: 1) conducted collaborative experiments with the ePOP and Swarm satellite missions to assess SuperDARN's capacity to identify the location of flow boundaries and examine trans-ionospheric HF propagation behaviour; 2) conducted joint operations with the Resolute Incoherent Scatter Radars (RISR-N, RISR-C); 3) developed new techniques to increase data quality and quantity, as well as to explore the production of new data products; 4) develop new VHF (ICEBEAR) and HF (Borealis) state-of-the-art radars; 5) and explore the occurrence behaviour of SuperDARN echoes.

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Koustov, A. V., D. B. Lavoie, and R. H. Varney (2016), On the consistency of the SuperDARN radar velocity and E × B plasma drift, Radio Sci., 51, doi:10.1002/2016RS006134.

Koustov, A.V., and R. A. D. Fiori (2016), Seasonal and solar cycle variations in the ionospheric convection reversal boundary location inferred from monthly SuperDARN data sets. Annales Geophysicae, 34, 227-239, doi:10.5194/angeo-34-227-2016.

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Malhotra, G., J. M. Ruohoniemi, J. B. H. Baker, R. E. Hibbins, and K. A. McWilliams (2016), HF radar observations of a quasi-biennial oscillation in midlatitude mesospheric winds, J. Geophys. Res. Atmos., 121, 12,677–12,689, doi:10.1002/2016JD024935.

Miles, D.M., I.R. Mann, D.J. Knudsen, K.A. McWilliams, K. Dahle, J. Grande, J. Moen, E.V. Thrane, A. Hansen, U.P. Lovhaug, I.J. Rae, A. Kale, B.J. Jackel, J.K. Burchill, A. Shahsavar, E.M. Grono, C. Cupido (2016), The Canada/Norway Student Sounding Rocket Program, Physics in Canada, 72:1, pp. 23—27.

Ponomarenko, P. V., B. Iserhienrhien, and J.-P. St.-Maurice. (2016). Morphology and possible origins of near-range oblique HF backscatter at high and midlatitudes. Radio Science. 51: 718-730.

St.-Maurice, J.-P. and J. L. Chau (2016), A theoretical framework for the changing spectral properties of meter-scale Farley-Buneman waves between 90 and 125 km altitudes, J. Geophys. Res. Space Physics, 121, doi:10.1002/2016JA023105.

Zhang, Q., J. Moen, M. Lockwood, I. McCrea, B. Zhang, K.A. McWilliams, Q. Zong, S. Zhang, J.M. Ruohoniemi, E.G. Thomas, M.W. Dunlop, R. Liu, H. Yang, H. Hu, M. Lester11 (2016), Polar cap patch transportation beyond the classic scenario, J. Geophys. Res. Space Physics, 121, 9063–9074, doi:10.1002/2016JA022443 (highlighted on cover)

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Akbari, H., L. V. Goodwin, J. Swoboda, J.-P. St.-Maurice, and J. L. Semeter (2017), Extreme plasma convection and frictional heating of the ionosphere: ISR observations, J. Geophys. 122, doi 10.1002/2017JA023916.

Laskar, F.I., J. L. Chau, J. P. St-Maurice, G. Stober, C. M. Hall, M. Tsutsumi, J.Höffner, and P. Hoffmann (2017), Experimental Evidence of Arctic Summer Mesospheric Upwelling and its

Connection to Cold Summer Mesopause, Geophys. Res. Lett, 44, 9151–9158, DOI: 10.1002/2017GL074759.

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Perry, G. W., H. G. James, R. G. Gillies, A. Howarth, G. C. Hussey, K. A. McWilliams, A. White, and A. W. Yau (2017), First results of HF radio science with e-POP RRI and SuperDARN, Radio Sci., 52, 78–93, doi:10.1002/2016RS006142.

Reimer, A.S., G.C. Hussey, and K.A. McWilliams, (2018). Statistically self-consistent and accurate errors for SuperDARN Data, Radio Science, accepted 28 December, 2017. 53, 93--111, https://doi.org/10.1002/2017RS006450, 2018.

Wu, J., Bryant, M. S., Ridley, C. G., Shen, Y., Yang, L., Clausen, L. B. N., McWilliams, K. A., Murphy, K. R., Mann, I. R., Ozeke, L. G., Korth, H., Anderson, B. J., Waters, C. L. (2017), A comparison of small-scale magnetic fluctuations in the region 1 and 2 field-aligned current systems, J. Geophys. Res. Space Physics, 122, 3277–3290, doi:10.1002/2016JA023453.

Zou, Ying, Yukitoshi Nishimura, Johnathan K. Burchill, David J. Knudsen, Larry R. Lyons, Kazuo Shiokawa, Stephan Buchert, Steve Chen, Michael J. Nicolls, J. Michael Ruohoniemi, Kathryn A. McWilliams, Nozomu Nishitani (2016), Localized Field-aligned Currents in the Polar Cap Associated with Airglow Patches, J. Geophys. Res. Space Physics, 121, doi:10.1002/2016JA022665.

4.2.4 RISR-C

The last quadrennial has seen the University of Calgary begin full operations of the Canadian (Southward) face of the Resolute Incoherent Scatter Radar (RISR-C). Early work using this system, in conjunction with the Northern face of the instrument (RISR-N), operated by SRI International, have focused on the study of ionospheric patches, field-aligned currents, and ion outflow. The RISR system is a phased array ISR capable of measuring plasma temperatures, densities, and drifts/electric fields over a large field of view within the polar cap and cusp regions.

Related Publications:

Zou, Y., Nishimura, Y., **Burchill, J.K., Knudsen,** D.J., Lyons, L.R., Shiokawa, K., Buchert, S., Chen, S., Nicolls, M.J., Ruohoniemi, J.M. and **McWilliams, K.A.**, Localized field-aligned currents in the polar cap associated with airglow patches. *J. Geophys. Res., 121* (10), 2016.

Ren, J., Zou, S., **Gillies**, R. G., **Donovan**, E., & Varney, R. H. (2018). Statistical characteristics of polar cap patches observed by RISR-C. Journal of Geophysical Research: Space Physics, 123, 6981–6995. https://doi.org/10.1029/2018JA025621

Gillies, R. G., **Perry**, G. W., **Koustov**, A. V., Varney, R. H., **Reimer**, A. S., **Spanswick**, E., et al. (2018). Large-scale comparison of polar cap ionospheric velocities measured by RISR-C, RISR-N, and SuperDARN. Radio Science, 53, 624–639. https://doi.org/10.1029/2017RS006435

Shen, Y., Knudsen, D.J., Burchill, J.K., Howarth, A., Yau, A., Redmon, R.J., **Miles, D.M.**, Varney, R.H. and Nicolls, M.J., Strong ambipolar-driven ion upflow within the cleft ion fountain during low geomagnetic activity. *J. Geophys. Res., 121* (7), pp. 6950 – 6969, 2016.

Gillies, R.G., Eyken, A., **Spanswick, E**., Nicolls, M., Kelly, J., **Greffen, M., Knudsen, D., Connors, M.**, Schutzer, M., Valentic, T. and Malone, M., First observations from the RISR-C incoherent scatter radar. *Radio Science, 51* (10), pp.1645 – 1659, 2016.

4.2.5 Transition Region Explorer (TREx)

The project consists of the development and deployment of an extensive ground-based network of sophisticated optical and radio instrumentation across Alberta, Saskatchewan, Manitoba, and the Northwest Territories.

The TREx project includes the design and deployment of the following instruments:

- 6 blue-line all-sky imagers (1s-30Hz cadence)
- 6 RGB colour all-sky imagers (3s cadence)
- 6 Near-Infrared all-sky imagers (3s cadence)
- 10 Imaging Riometers (1s-100Hz cadence - operations project is GO-IRIS)
- Proton Aurora Meridian Imaging Spectographs (30s cadence)
- 13 Global Navigation Satellite System receiver systems (GNSS)

In partnership with IBM, TREx will include sensor web technology to autonomously control and coordinate sensor behaviour across the observational region. This architecture will allow TREx to produce the first high resolution data (estimated at 120 TB of data per year) over a region large enough to study multi-scale coupling of key physical processes in the space environment. The project is currently at the deployment and testing phase.

4.2.6 THEMIS

The ground-based THEMIS All Sky Imager (ASI) array has continued to provide high quality data and related research outcomes.

Related Publications:

Grono, E. and **Donovan**, E.: Differentiating diffuse auroras based on phenomenology, Ann. Geophys., 36, 891-898, https://doi.org/10.5194/angeo-36-891-2018, 2018.

Archer, W. E., D. J. **Knudsen**, J. K. **Burchill**, B. **Jackel**, E. **Donovan**, M. **Connors**, and L. Juusola (2017), Birkeland current boundary flows, J. Geophys. Res. Space Physics, 122, 4617–4627, doi:10.1002/2016JA023789.

Yang, B., **Donovan**, E., **Liang**, J., and **Spanswick**, E.: A statistical study of the motion of pulsating aurora patches: using the THEMIS All-Sky Imager, Ann. Geophys., 35, 217-225, https://doi.org/10.5194/angeo-35-217-2017, 2017.

Grono, E., **Donovan**, E., and Murphy, K. R.: Tracking patchy pulsating aurora through all-sky images, Ann. Geophys., 35, 777-784, https://doi.org/10.5194/angeo-35-777-2017, 2017.

Lyons, L. R., et al. (2016), The 17 March 2013 storm: Synergy of observations related to electric field modes and their ionospheric and magnetospheric Effects, J. Geophys. Res. Space Physics, 121, 10,880–10,897, doi:10.1002/2016JA023237.

Nishimura, Y., J. **Yang**, P. L. Pritchett, F. V. Coroniti, E. F. **Donovan**, L. R. Lyons, R. A. Wolf, V. Angelopoulos, and S. B. Mende (2016), Statistical properties of substorm auroral onset beads/rays, J. Geophys. Res. Space Physics, 121, 8661–8676, doi:10.1002/2016JA022801.

Motoba, T., S. Ohtani, E. F. **Donovan**, and V. Angelopoulos (2015), On a possible connection between the longitudinally propagating near-Earth plasma sheet and auroral arc waves: A reexamination, J. Geophys. Res. Space Physics, 120, 432–444, doi:10.1002/2014JA020694.

Zou, Y., Y. Nishimura, L. R. Lyons, E. F. **Donovan**, K. Shiokawa, J. M. Ruohoniemi, K. A. **McWilliams**, and N. Nishitani (2015), Polar cap precursor of nightside auroral oval intensifications using polar cap arcs, J. Geophys. Res. Space Physics, 120, 10,698–10,711, doi:10.1002/2015JA021816.

Liang, J., E. **Donovan**, Y. Nishimura, B. **Yang**, E. **Spanswick**, K. Asamura, T. Sakanoi, D. Evans, and R. Redmon (2015), Low-energy ion precipitation structures associated with pulsating auroral patches, J. Geophys. Res. Space Physics, 120, 5408–5431, doi:10.1002/2015JA021094.

4.2.7 Modeling

Related Publications:

Kabin, K., G. Kalugin, E. Donovan, and E. Spanswick (2017), Particle energization by a substorm dipolarization, J. Geophys. Res. Space Physics, 122, 349–367, doi:10.1002/2016JA023459.

Sydorenko, D. and R. **Rankin** (2017), The stabilizing effect of collision-induced velocity shear on the ionospheric feedback instability in Earth's magnetosphere, Geophys. Res. Lett., 44, 6534–6542, doi:10.1002/2017GL073415.

Hao, Y. X., Q.-G. Zong, X.-Z. Zhou, R. **Rankin**, X. R. Chen, Y. Liu, S. Y. Fu, H. E. Spence, J. B. Blake, and G. D. Reeves (2017), Relativistic electron dynamics produced by azimuthally localized poloidal mode ULF waves: Boomerang-shaped pitch angle evolutions, Geophys. Res. Lett., 44, 7618–7627, doi:10.1002/2017GL074006.

Artemyev, A. V., R. **Rankin**, and I. Y. Vasko (2017), Nonlinear Landau resonance with localized wave pulses, J. Geophys. Res. Space Physics, 122, 5519–5527, doi:10.1002/2017JA024081.

Ren, J., Q. G. Zong, X. Z. Zhou, R. **Rankin**, and Y. F. Wang (2016), Interaction of ULF waves with different ion species: Pitch angle and phase space density implications, J. Geophys. Res. Space Physics, 121, 9459–9472, doi:10.1002/2016JA022995.

Turkakin, H., R. **Rankin**, and I. R. Mann (2016), Emission of magnetosound from MHD-unstable shear flow boundaries, J. Geophys. Res. Space Physics, 121, 8740–8754, doi:10.1002/2016JA022816.

Artemyev, A. V., R. **Rankin**, and I. Y. Vasko (2016), Upper limit of electron fluxes generated by kinetic Alfvén waves in Maxwellian plasma, J. Geophys. Res. Space Physics, 121, 8361–8373, doi:10.1002/2016JA023076.

Zhou, X.-Z., Z.-H. Wang, Q.-G. Zong, R. **Rankin**, M. G. Kivelson, X.-R. Chen, J. B. Blake, J. R. Wygant, and C. A. Kletzing (2016), Charged particle behavior in the growth and damping stages of ultralow frequency waves: Theory and Van Allen Probes observations, J. Geophys. Res. Space Physics, 121, 3254–3263, doi:10.1002/2016JA022447.

Artemyev, A. V., R. **Rankin**, and M. Blanco (2015), Electron trapping and acceleration by kinetic Alfven waves in the inner magnetosphere, J. Geophys. Res. Space Physics, 120, 10,305–10,316, doi:10.1002/2015JA021781.

Gharaee, H., R. **Rankin**, R. Marchand, and J. Paral (2015), Properties of the lunar wake predicted by analytic models and hybrid-kinetic simulations. J. Geophys. Res. Space Physics, 120, 3795–3803. doi: 10.1002/2014JA020907.

Wang, C., R. **Rankin**, and Q. Zong (2015), Fast damping of ultralow frequency waves excited by interplanetary shocks in the magnetosphere. J. Geophys. Res. Space Physics, 120, 2438–2451, doi: 10.1002/2014JA020761.

4.2.8 CaNoRock and CaNoSat Student Programs

The Canada-Norway Student Sounding Rocket (CaNoRock) and subsequent Canada-Norway Student Satellite (CaNoSat) Programs are multi-university collaborations to train undergraduate students in space science or engineering, and to recruit them into space related graduate studies or industry.

CaNoSat aims to build and launch five 3-unit CubeSats in a ten year timespan. This will allow uptake of new students every two years to start on a new satellite mission.

Canadian students will be able to spend at least half a year in Norway, and the Norwegian students are expected to stay at least half a year in Canada, which may be for internship and/or academic training. The space mission training will be the basis for the project work as part of a Master of Science degree in Physics, Informatics or Engineering.

Related Publications:

Miles, D.M., Mann, I.R., Knudsen, D.J., McWilliams, K.A., Dahle, K., Grande, J., Moen, J., Thrane, E.V., Hansen, A., Løvhaug, U.P., **Burchill, J.K.**, Rae, I.J., Kale, A., **Jackel, B.**, Shahsavar,

A., **Grono, E.**, Cupido, C., The Canada/Norway Student Sounding Rocket Program (CaNoRock), *Physics in Canada, 72*, 1, 23 – 27, 2016.

4.2.9 Citizen Science Initiatives and Outcomes

Of particular note over the past quadrennial was the discovery of STEVE, later defined as "Strong Thermal Emission Velocity Enhancement", through the collaborative efforts of scientists at the University of Calgary and amateur aurora chasers. STEVE's discovery resulted in significant media attention, particularly due to the necessary involvement of civilian aurora chasers in the discovery. Subsequently, citizen science programs have begun appearing within the community, such as Aurorasaurus (http://www.aurorasaurus.org/), an aurora tracking tool that monitors social media and other platforms for reports of observed aurora.

Related Publications:

MacDonald EA, Donovan E, Nishimura Y, Case NA, **Gillies** DM, **Gallardo-Lacourt** B, **Archer** WE, **Spanswick** EL, Bourassa N, **Connors** M, Heavner M, **Jackel** B, Kosar B, **Knudsen** DJ, Ratzlaff C, Schofield I. (2018) New science in plain sight: Citizen scientists lead to the discovery of optical structure in the upper atmosphere. Sci Adv. 2018 Mar 14 ; 4(3).

Gallardo-Lacourt, B., **Liang**, J., Nishimura, Y., & **Donovan**, E. (2018). On the origin of STEVE: Particle precipitation or ionospheric skyglow? Geophysical Research Letters, 45, 7968–7973. https://doi.org/10.1029/2018GL078509

Gallardo-Lacourt, B., Nishimura, Y., **Donovan**, E., **Gillies**, D. M., **Perry**, G. W., **Archer**, W. E., et al. (2018). A statistical analysis of STEVE. Journal of Geophysical Research: Space Physics, 123, 9893–9905. https://doi.org/10.1029/2018JA025368

4.3 Conference and Meeting Participation

The Canadian space community was very active over the quadrennial, with over two thousand presentations conducted by Canadian scientists nationally and internationally over the 2016-2018 period alone. This is provided in detail in Table 4.

Table 4. Summary of Canadian Space Science presentations for the 2016-2017 and 2017-2018 years (statistics unavailable for 2015-2016 and 2018-2019).

Presentations	2016-2017 Number of Presentations	2017-2018 Number of Presentations
Conference/Seminar and Workshop Presentations	696	942
Media/General Public Presentations	115	189
Other	151	141

A list of these conferences is provided below:

- American Geophysical Union Fall Meeting: San Francisco CA, December 2015; San Francisco CA, December 2016; New Orleans LA, December 2017; Washington DC, December 2018
- Canadian Association of Physicists (CAP) Congress, 2015, 2016, 2017, and 2018
- Asia Oceania Geosciences Society (AOGS) Meeting: Singapore, August 2015; Beijing, China, August 2016; Singapore, August 2017; Honolulu HI, June 2018
- European Geosciences Union (EGU) General Assembly: Vienna, Austria, April 2015; April 2016; April 2017; April 2018
- URSI Atlantic Radio Science Conference (URSI AT-RASC), Mas Palomas, 2015, 2018
- International Committee of Space Research (COSPAR) 42nd Assembly, Pasadena CA, July 2018
- Cluster-THEMIS Team Meeting, Chaniá, Greece, September 24-28 2018
- SCOSTEP Quadrennial Meeting 2018
- Whole Atmosphere Model Workshop 2018
- CANSSI Closeout Meeting, Queen's University, August, 2018
- 2018 International Astronomy Teaching Summit Conference, July 25-27, 2018, Hilo, Hawai'i
- CASCA, Victoria, 22-26 May 2018
- TESS, Leesburg Virginia, May 2018
- e-POP Science Team Meeting #18, Saskatoon SK, Feb. 22 2018
- Fundamental Physical Processes in Solar-Terrestrial Research and Their Relevance to Planetary Physics 2018, Kona, Hawai'I, January 2018
- American Association of Physics Teachers, San Diego, January 2018
- POLAR2018, Davos, Switzerland, June 2018
- 2017 International Ionospheric Effects Symposium (IES), Alexandria, VA
- 32nd International Union of Radio Science (URSI) General Assembly and Scientific Symposium, Montreal, Canada, 19--26 August, 2017
- SWARM Science Meeting 2017
- 2017 International Space Weather Meridian Circle Program Workshop, Qingdao, China, May 14-18, 2017
- JpGU-AGU Joint Meeting 2017, Makuhari Messe, Japan, May 2017
- 13th International Conference on Substorms, Portsmouth NH, September 2017
- 19th colloquium of the Center for International Collaborative Research (CICR) of the Institute for Space-Earth Environmental Research (ISEE), Nagoya University, Feb. 10, 2017
- PSTEP-2, Kyoto, March 23-24, 2017
- 2017 International Conference on Education and Multimedia Technology, Singapore, July 9-11, 2017
- IAPSO-IAMAS-IAGA Joint Assembly, Cape Town, South Africa, August 2017
- Magnetosphere-Ionosphere Symposium, Nishijin Plaza, Kyushu University, Fukuoka, Japan, 15 March 2017
- Research meeting "Observation and Modeling of Plasmasphere", Osaka Electro Communication University, 6-7 March 2017
- SuperDARN Workshop, San Quirico d'Orcia, Italy, June 4-9, 2017
- Swarm 7-th Data Quality Workshop, Oct 24-27, 2017, Delft University of Technology, Delft, Netherlands.
- Symposium of Space Science and Radio Engineering, 14-15 Feb 2017, Univ. of Electro-Communications, Tokyo, Japan.

- USNC-URSI NRSM (National Radio Science Meeting), Boulder, CO, USA, 4—7 January, 2017.
- 2017 International Reference Ionosphere Workshop, Taiwan
- International Center for Theoretical Physics (ICTP) Radio Science School, 2017
- Living Planet Symposium, Prague, Czech Republic, May 2016
- Undergraduate Research in Science Conference of Alberta, 2 April 2016
- AOGS Annual Meeting 2016
- VarSITI General Symposium 2016
- e-POP Science Meeting/Workshop 2015 and 2016
- American Astronomical Society 227 Meeting, Kissimmee, FL, 4-8 January 2016
- American Association of Physics Teachers, New Orleans, Jan. 9-12, 2016
- Government of Canada's "Big Science Infrastructure" Round Table, as part of "Canada's Fundamental Science Review Panel," Calgary, AB, Sept 29, 2016
- SuperDARN Workshop, Fairbanks, Alaska, USA, May 29-June 3, 2016
- Swarm Science Meetings, 9-13 May 2016, Prague
- 2015 International Space Weather Workshop and Training: Extreme Events and Their Effects on Power Systems, Ottawa, 18-20 March 2015
- Environment Canada (EC), Natural Resources Canada (NRCan), and Canadian Space Agency (CSA) workshop on ionosphere-atmosphere models 2015
- IUGG 26th General Assembly, Prague, Czech Republic, June 2015
- Canadian Statistical Sciences Institute, La Petite Rouge, Québec 18 October 2015
- GO Canada Kickoff Meeting, Calgary, 17 February 2015
- American Association of Physics Teachers, San Diego, USA, 3-6 January, 2015
- CEDAR-GEM Workshop, Seattle 2015, Albuquerque 2016, Boulder 2017
- 2015 International Space Weather Workshop and Training: Extreme Events and Their Effects on Power Systems, Ottawa, Ontario, Mar 16-20, 2015
- Annual international SuperDARN workshop, Leicester, England, May 2015
- Canadian Annual Solar Workshop, La Petite Rouge, Quebec, October 16, 2015.
- e-POP Science Team Meeting #16, University of Calgary, Calgary, Alberta, 18—19 February, 2015
- Joint assembly of the American Geophysical Union, GAC-MAC-CGU, Palais des Congres de Montreal, May 2015
- Prairie Universities Physics Seminar Series (PUPPS) Lecture, University of Regina, Department of Physics, Nov 27, 2015
- Royal Astronomical Society Meeting on Current and future research with the Super Dual Auroral Radar Network, Nov 13, 2015, Royal Astronomical Society, Burlington House, Piccadilly, London, UK
- Workshop to Honor Donald T. Farley on the Occasion of his 80th Birthday and to Consider the Future of Radio and Space Physics, Snee Hall, Cornell University March 30 – April 1, 2015
- Measurement Techniques in Solar and Space Physics, Boulder, 2015
- 2015 International Reference Ionosphere Workshop, Bangkok

Corresponding publications summaries for 2016-2018 are provided in Table 5.

Table 5. Summary of Canadian Space Science publications for the 2016-2017 and 2017-2018 years (statistics unavailable for 2015-2016 and 2018-2019).

Publication Type	2016-2017 Number of Publications	2017-2018 Number of Publications
Peer Reviewed Publications	403	514
Non-Peer Reviewed Publications	144	79
Books	11	5
Research or Technical Reports	30	45

4.4 Awards

- Dr. A. M. McCaffrey - URSI Young Scientist Award, 2018 (AT-RASC)
- Dr. L. Goodwin, winner of the Ishwar Gupta Dissertation Prize in Physics & Engineering Physics (USask), 2018
- Dr. C. Watson - URSI Young Scientist Award, 2017 (GASS)
- Dr. D.R. Themens - Prof. Reinhold and Maria Kaiser Memorial Prize in Physics (UNB), 2017
- Dr. D.R. Themens - URSI 2017 GASS Student Paper Competition Finalist - Honourable Mention
- Dr. D.R. Themens - URSI Young Scientist Award, 2015 (AT-RASC) and 2017 (GASS)
- Dr. L. Goodwin - URSI Young Scientist Award, 2017 (GASS)
- SuperDARN International was awarded The Group Achievement Award for achievement by a large consortium in geophysics from the Royal Astronomical Society (RAS). 2017
- MSc graduate Matthew Wessel won the University of Saskatchewan's Graduate Thesis Award (Master's) in the Physical and Engineering Sciences. 2017
- Dr. A. Reimer, PhD, winner of the Harry Toop Memorial Prize in Scientific Writing at the University of Saskatchewan
- Alberta Science and Technology Leadership (ASTech) Foundation Special Group Award for Outstanding Contributions to Canadian Space Industry, Oct 2018 (presented to the Space Physics Group at the University of Calgary).
- Dr. Gordon Shepherd was honoured with the SCOSTEP Distinguished Research Scientist award in 2014 and the COSPAR William Nordberg Medal in 2016.

4.5 Research Personnel

Research personnel summaries for the 2016-2017 and 2017-2018 years are provided in Figure 1 and Figure 2, respectively.

Research Team	Number of Research Team Members
Research Chair / Industrial Chair	49
Tenured Faculty	284
Non-Tenured Faculty	62
Research Associate	162
FACULTY	**557**
Post-Doctoral Fellow	92
Graduate Student	262
Under-graduate Student	104
Other Students	14
STUDENTS & Post-Doctoral Fellows	**472**
Scientists	82
Engineers	82
Technicians	61
Research Assistant	34
Other personnel	31
OTHER Than Students	**290**

Figure 1. Personnel within the Canadian space science community in 2016-2017.

Research Team	Number of Research Team Members
Research Chair / Industrial Chair	54
Tenured Faculty	384
Non-Tenured Faculty	69
Research Associate	89
FACULTY	**596**
Post-Doctoral Fellow	125
Graduate Student	299
Under-graduate Student	218
Other Students	22
STUDENTS & Post-Doctoral Fellows	**664**
Scientists	110
Engineers	88
Technicians	70
Research Assistant	30
Other personnel	37
OTHER than students (or Private Sector)	**335**

Figure 2. Personnel within the Canadian space science community in 2017-2018.

4.6 Conclusions

The Canadian Space Science Community has repeatedly produced strong and impactful research recognized around the world. The community's unique deployment of overlapping and complementary ground-based observation networks has positioned the community for international collaboration through high impact direst research and ground-based instrument support for satellite missions. In addition to ground-based observations, the community launched a successful smallsat mission, which has received international recognition, and is highly involved in the European Space Agency Swarm and SMILE missions. Despite this success, as with any research community, science funding, particularly for operational purposes, is always challenging and a reduction of researcher and tenured faculty renewal at Canadian Universities is posing a significant challenge to the community. In spite of the community's view of ground-based instruments as a unique asset of the Canadian community, funding for ground-based instrument networks has become increasingly challenging to acquire, with funding agencies having to be regularly reminded that space programs do not preclude the need for ground instrument support and that space mission outcomes can be significantly enhanced through complimentary instrument support. Also, a lack of regular, scientifically viable spaceflight opportunities in Canada, especially for student training (e.g. cubesats) has arisen as a point of frustration for many within the community. International collaborations for such activities are highly of interest; however, a lack of adequate project support has resulted in many missed opportunities.

Section 3 International Association of Hydrological Sciences (IAHS)

The Canadian National Committee for the International Association of Hydrological Sciences (CNC/IAHS)

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1) Description of CNC-IAHS

During the period 2014 to 2018, activities of the CNC/IAHS were largely supported by the Hydrology Section of the Canadian Geophysical Union (CGU-HS). The CGU-HS consults with the Canadian hydrological community and maintains the composition of the CNC/IAHS Executive and mandate of CNC/IAHS.

The roles and objectives of the CNC/IAHS are defined as follows:

a. to promote and support hydrology as a geoscience within National and among International communities;
b. to encourage and promote the collaboration between IAHS and Canadian scientific organizations and institutions;
c. to encourage and promote the participation of Canadian scientists in IAHS and its activities;
d. to initiate cooperative research and education programs in hydrology with IAHS;
e. to respond, on behalf of Canada, to scientific requests from IAHS;
f. to undertake the dissemination and transfer of information on IAHS-related activities among Canadian hydrologists;
g. to seek and support the nomination of Canadian hydrologists to Executive positions of IAHS; and
h. to arrange the selection and nomination of National Representatives to IAHS, IAHS Commissions and Committees.

The first CNC/IAHS Annual Meeting was held in Quebec City in May 1998. In 2018, the CNC/IAHS Executive from consisted of:

- Chair, R.M. Petrone, University of Waterloo, Canadian Senior Representative to IAHS;
- G. Ali, University of Guelph, Canadian Junior Representative to IAHS and Secretary;
- CGU-HS President, C. Oswald, Ryerson University;
- CGU-HS Vice-President, Andrew Ireson, University of Saskatchewan.

The CNC/IAHS has historically concentrated on three main topics. The first concerns the dissemination of information on the goals and *modus operandi* of the committee to the Canadian hydrological community and the consolidation of contacts and collaboration with the member organizations of the committee itself. The second topic is the strengthening of Canadian participation in IAHS by nominating candidates for office in the IAHS Bureau and in the bureaus of its constituent Scientific Commissions and Committees for the General assembly of IUGG. The CNC/IAHS also manages a selection process for the delegation of Canadian National Representatives (CNR) to IAHS and to the IAHS Commissions and

Committees. The third consists of preparing the report on Canadian hydrology as a contribution to this CNC/IUGG Quadrennial Report.

2) Institutions and individuals involved in IAHS-related research

Within CGU and CNC-IAHS, activities that are aligned with the IAHS mandate are mostly carried out by members in the areas of Hydrology, Biogeosciences and Earth Surface Processes. In 2018, 227 Canada-based scientists registered as CGU members while declaring the Hydrology Section, the Biogeosciences Section or the Earth Surface Processes Section as their primary affiliation (Table 1). Those numbers vary from year to year (including between 2014 and 2018) and are only provided for 2018, here, for illustration purposes. Of the 227 CGU members registered in 2018, 99 were students. The 227 identified CGU members in 2018 are listed in Appendix A and belong to educational institutions as well as industry, government departments and non-governmental organizations (Figure 1).

Table 1. CGU members carrying activities aligned with the IAHS mandate in 2018.

	IAHS-related CGU Sections		
	Hydrology	**Biogeosciences**	**Earth Surface Processes**
Members: Total	143	47	37
Members: Regular	76	26	26
Members: Student	67	21	11

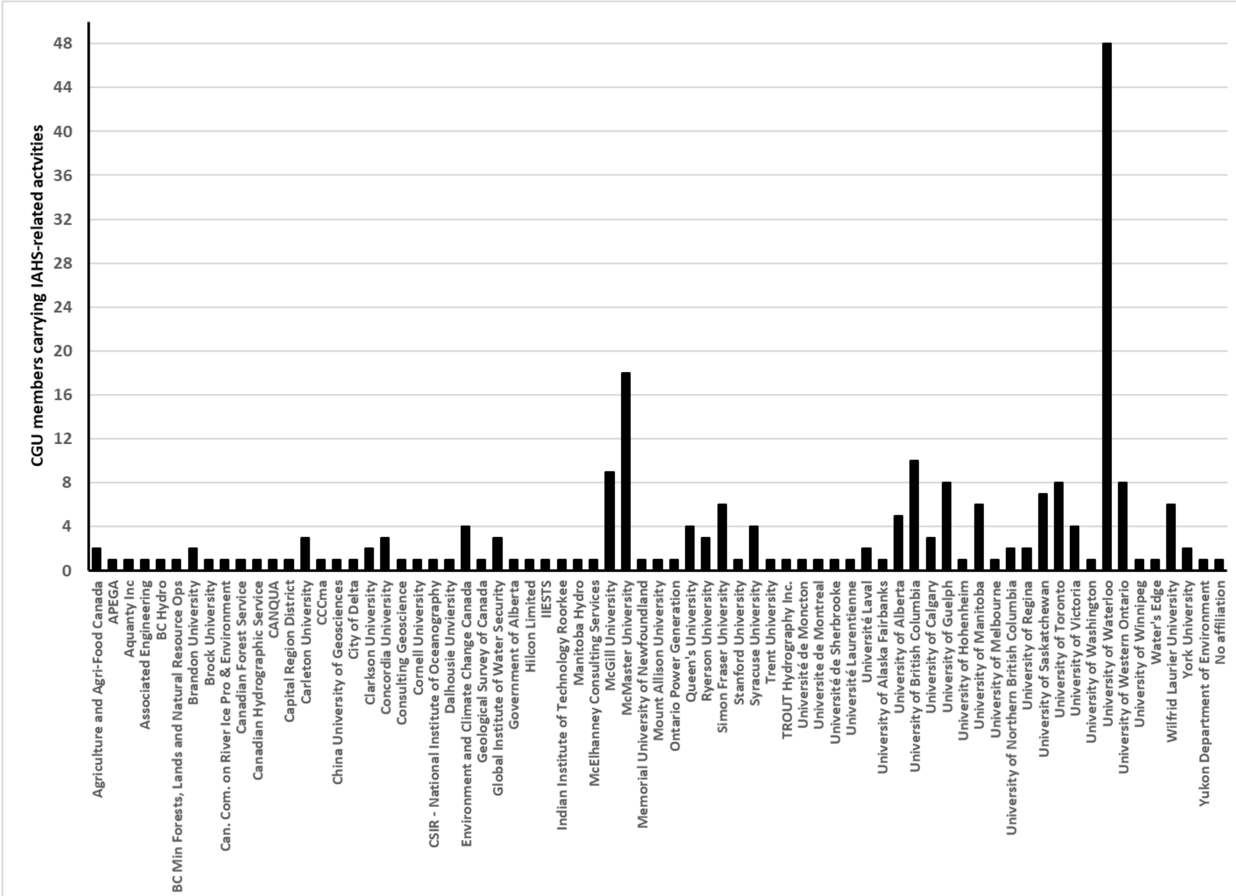

Figure 1. Home institutions or organizations of CGU members carrying activities aligned with the IAHS mandate (based on 2018 CGU membership data only).

3) Research activities

** Please note that the current report on research activities is, by no means, exhaustive. The information included is only meant to be indicative of the breadth of water-related research in Canada.*

3.1) Major research areas

Established in 1993, the Canadian Geophysical Union - Hydrology Section (CGU-HS) brings together scientists from all branches of hydrology and represents the largest organization of academic and research hydrologists in the country. Its aims and objectives are to: (i) promote hydrology as a geophysical science; (ii) advance the understanding and application of hydrology and related sciences; (iii) initiate and participate in research and education programs in hydrology; (iv) promote national and international cooperation among scientific and engineering organizations working in hydrology; and (v) disseminate research results and knowledge to the public through scientific discussion, meetings and conferences, publications and other means of information and technology transfer. As previously mentioned, the Hydrology Section acts as the umbrella organization for the CGU/IAHS Nominating Committee. More information about CGU-HS can be found at http://www.cgu-hs.ca/. To foster ideas among its members and highlight emerging areas of hydrological research in Canada, CGU-HS encourages its members to propose and maintain technical committees on specific topics. Those committees not only serve as an natural venue for like-minded researchers to connect, but they also provide CGU-HS with a mechanism thanks to which reports on all Canadian activities taking place in a given research area are submitted annually. As of 2018, CGU-HS relied on eight committees, namely:

- The Committee on River Ice Processes and the Environment (CRIPE)
- The Northern Research Basins Committee
- The Committee on Isotope Tracers
- The Hydroecology Committee
- The Urban Hydrology Committee
- The Canadian Young Hydrologic Society
- The Committee on Hydro-climatic Impacts and Adaptation
- The Committee on Large Scale Watershed Modelling and Analysis

3.2) Research chairs

Research chairs are extremely prestigious appointments at the university, provincial or national levels and are meant to recognize both the emerging and critical nature of a particular research area, as well as the exceptional potential or curriculum of the chair holder. For the sake of brevity, the current report only focuses on research chair proposals adjudicated by NSERC (Natural Sciences and Engineering Research Council of Canada), which is the largest, nation-wide funding agency for research aligned with the mandate of IAHS. While NSERC awards different types of research chairs, worthy of note are the Canada Research Chairs (CRCs), the Canada Excellence Research Chairs (CERCs), and the Canada 150 Research Chairs.

The CRC program was put forward in 2000 as a way to retain outstanding scholars and scientists in Canada across all disciplines. Tier 1 CRCs are tenable for seven years and renewable once; with funding of CAD 200,000 annually during the tenure period, Tier 1 CRCs are awarded to outstanding researchers whom their peers have identified as world leaders in their fields. Tier 2 CRCs are rather tenable for five years, renewable once, with funding of CAD 100,000 annually during the tenure period; they are meant to recognize exceptional emerging researchers. A number of CGU, CWRA, CMOS and CCIAH members have been highly successful in the latest CRC competitions. Between 2014 and 2018, 23 CRCs aligned with the IAHS mandate were active (Table 2).

Table 2. Canada Research Chairs (CRCs) with focal areas aligned with the IAHS mandate that were active between 2014 and 2018.

Canada Research Chair in…	**Chair holder**
Hydrology and Remote Sensing	Berg, Aaron
Environment and Sustainability	Branfireun, Brian
Environmental Modelling and Analysis	Craig, James
Watershed Sciences	Creed, Irena
River Ecosystem Science	Cunjak, Richard
Northern Hydrometeorology	Dery, Stephen

Source Water Protection	Dorner, Sarah
Glacier Hydrology and Ice Dynamics	Dow, Christine
Physical Hydrology	Hayashi, Masaki
Watershed Analysis and Modeling	James, April
Environmental Sustainability	Ketcheson, Scott
Water and Health	Kim, Younggy
Cryosphere Hydrology	Kinnard, Christophe
Future Water Services	Liu, Yang
Cold Regions Water Science	Marsh, Philip
Environmental Biogeochemistry	O'Driscoll, Nelson
Water Resources and Climate Change	Pomeroy, John
Cold Regions Hydrology and Water Resources	Quinton, William
Water Quality Protection	Servos, Mark
Atmospheric Biogeosciences at High Latitudes	Sonnentag, Oliver
Ecosystem and Climate	Strack, Maria
Ecohydrology	Waddington, James

The CERC program is more recent than the CRC program and also has a different target: launched in 2008, it does not aim to retain scholars and scientists in Canada but rather to recruit world-renowned researchers and their teams from abroad and have them move to Canada so that they can contribute to "*Canada's growing reputation as a global leader in research and innovatio*n". CERCs are tenable for seven years with a funding envelope of CAD 10 millions. Between 2014 and 2018, two CERC laureates carried out activities that strongly aligned with the mandate of IAHS, namely Philippe Van Cappellen with the CERC in Ecohydrology, and Howard Wheater with the CERC in Water Security. Lastly, the newly minted Canada 150 Chairs program, which was launched around the 150th birthday of Canada, has also provided significant funding (CAD 7 millions over 7 years) to attract Jay Famiglietti to Canada in 2018 as a Chair in Hydrology and Remote Sensing.

3.3) Science-industry collaborations

NSERC has several funding programs that promote science-industry collaborations, including Industrial Research Chairs (IRCs) and Collaborative Research and Development (CRD) Grants. Similar to CRCs, IRCs are very prestigious appointments meant to help individuals and research institutions undertake major research endeavours that are of great interest to industry. The focus of IRCs is typically on the development of knowledge, expertise, research infrastructure or highly qualified personnel that are crucially needed by industry but not yet development in Canadian universities. Thus, IRC appointments are meant to create mutually beneficial collaborations between Canadian universities and either public or private sector partners, this in the hope of creating economic, social and/or environmental benefits for Canadians. Table 3 shows that CGU, CWRA, CMOS and CCIAH members carrying hydrological science activities have been successful in being awarded IRCs.

Table 3. Industrial Research Chairs (IRCs) with focal areas aligned with the IAHS mandate that were active between 2014 and 2018.

IRC	Chair Holder
NSERC Industrial Research Chair in Source Water Quality Monitoring and Advanced/Emerging Technologies for Drinking Water Treatment	Andrews, Robert
NSERC/Manitoba Hydro Industrial Research Chair in River Ice Engineering	Clark, Shawn
NSERC/Hydro-Québec Industrial Research Chair in Carbon Biogeochemistry in Boreal Aquatic Systems	DelGiorgio, Paul
NSERC Industrial Research Chair in Fate and Transport of Reactive Solutes Diffusion-Dominated Systems	Hendry, James
NSERC Industrial Research Chair on the Application of Hydrometeorological Data from Satellite Images To Improve Hydrological Forecasting	Leconte, Robert
NSERC Industrial Research Chair in Groundwater Contamination in Fractured Media	Parker, Beth
NSERC Industrial Research Chair in Management and Surveillance of Drinking Water Quality from the Watershed to the Citizen's Tap	Rodriguez, Manuel
NSERC Industrial Research Chair in Urban Drainage	Zhu, David

CRD grants also provide Canadian researchers with the means to pursue research collaborations with private or public sector partners on a project-specific basis. With a maximum funding envelope of CAD 1 million over five years, formalized science-industry research collaborations can focus on solving a natural sciences or engineering challenge, as long as the proposed activities have clear and measurable short- to medium-term objectives. As illustrated in Table 4, CGU, CWRA, CMOS and CCIAH members carrying hydrological research have, also, been very successful in competing for CRD grants, Canada-wide.

Table 4. Select CRD grant projects with research topics aligned with the IAHS mandate that were active between 2014 and 2018.

CRD grant topic	Principal investigator
BaySys - Contributions of climate change and hydro-electric regulation to the variability and change of freshwater-marine coupling in the Hudson Bay system	Barber, David
Lot-level practices to control urban flood risk and mitigate basement flooding in Canada	Binns, Andrew
Scientific and operational value of alternative datasets in hydrological science	Brissette, Francois
Understanding the impact of coal spoils on the hydrology of alpine watersheds, Elk Valley, British Columbia	Carey, Sean
Applying natural analogues to constructing and assessing long-term hydrological response of oil sands reclaimed landscapes	Devito, Kevin
Streamflow prediction at ungauged remote sites	Gharabaghi, Bahram
The next generation water tool for managing surface and groundwater conjunctively across jurisdictions	Gleeson, Tom
Role of terrestrial carbon and base cations in the recovery of damaged aquatic systems	Gunn, John
A monitoring framework to assess changes in hydroecological conditions, and sources, distributions and toxicity of contaminants in lakes of the Peace-Athabasca delta	Hall, Roland
Evaluation of hydraulic tomography and data integration for improved estimates of subsurface hydraulic parameters	Illman, Walter
Quantifying salt release from oil sands reclamation covers	Ireson, Andrew
Development of a UAV-based multispectral camera for precision agriculture	Leblon, Brigitte

CRD grant topic	Principal investigator
applications	
Quantifying the effects of freeze-thaw cycles on mine cover system design and performance	McDonnell, Jeffrey
Evaluating the success of fen creation in the post oil sands landscape	Price, Jonathan
Carbon and nitrogen fluxes in reconstructed oil sands soils	Quideau, Sylvie
Consortium for Permafrost Ecosystem in Transition (CPET)	Quinton, William
Adaptation and application of the Canadian Precipitation Analysis (CaPA) in Manitoba	Rasmussen, Peter
Influence of Ice Processes on fluvial sediment transport	Rennie, Colin
Development of methods and tools for the integrated management of drinking water quality	Rodriguez, Manuel
Inflow forecasting in Yukon under current and changing climate conditions	Rousseau, Alain
Development of autonomous radar for remotely measuring snow and ice thickness over lakes and rivers	Royer, Alain
Practical and direct downscaling of water level projections for adaptation planning	Sauchyn, David
Supporting adaptation planning in the Athabasca River Basin with advances in the projection of hydroclimatic variability	Sauchyn, David
Future hydroclimatic extremes and adaptive basin planning, Oldman and South Saskatchewan river basins	Sauchyn, David
Water quality in the lower Athabasca River	Shotyk, William (Bill)
Développement et adaptation d'un outil multi-modules de prévision hydrologique et thermique dans un contexte d'assimilation de données	St-Hilaire, André
Evaluating ecological restoration outcomes for oil sand well-site disturbances on peatland: linking ecosystem structure and function	Strack, Maria
A regional climate modelling system for climate/hydrology process and feedback studies	Sushama, Laxmi
Laboratory studies investigating chemical flux across tailings-cap water zones, simulating an End Pit Lake in the Athabasca oil sands region	Ulrich, Ania
The effects of reforestation on forest carbon and water coupling at multiple spatial scales	Wei, Adam
Sediment and nutrient transport and fate in stormwater wet ponds and constructed wetlands	Zhu, David

3.4) Training and networking initiatives geared towards young and emerging scientists

While there are many different training and networking activities that could be discussed here, the present report only focuses on four types of programs or initiatives, namely: NSERC CREATE programs, CWRA-led short courses, an ad-hoc team science training initiative geared towards undergraduate students, and events led by the Canadian Young Hydrologic Society (CYHS).

CREATE (Collaborative Research and Training Experience) grants are alike any other, in Canada, as their sole aim is to support the training of students – mostly at the M.Sc. and Ph.D. levels – and postdoctoral fellows through innovative programs. Between 2014 and 2018, several CREATE awards were made to CGU, CWRA, CMOS and CCIAH members to provide enhanced training to students in hydrological research, with specific training topics that ranged from knowledge to address the algal bloom crisis, to issues of water security and sanitation for First Nations. Select CREATE award details are listed in Table 5.

Table 5. <u>Select</u> NSERC CREATE training with focal areas aligned with the IAHS mandate that were active between 2014 and 2018.

Training program	**Principal investigator**
NSERC CREATE Program in Training strategies to meet the challenges imposed by a changing climate: preparing for societal impacts and adaptation	Beltrami, Hugo
NSERC CREATE for freshwater Harmful Algal Blooms (fHABs): Algal Bloom Assessment though Science, Technology and Education (ABATE).	Creed, Irena
NSERC CREATE for Watershed and Aquatics Training in Environmental Research (WATER)	Curry, Ranald
NSERC CREATE Training Program in Aquatic Ecosystem Health: Integrative Approaches for Studying Multiple Stressors (ERASMUS)	Drouillard, Ken
NSERC CREATE Program for Water and Sanitation Security in First Nations (H2O CREATE)	Farenhorst, Annemieke
NSERC CREATE Research and Training via an Institute in Water, Energy and Sustainability	Mulligan, Catherine
Multiple Stressors and Cumulative Effects in the Great Lakes: An NSERC CREATE program to Develop Innovative Solutions through International Training Partnerships	Sibley, Paul
NSERC CREATE for Water Security	Westbrook, Cherie

CWRA also sponsors two short courses, which are offered annually in specific locations but are open to both graduate students and water resource professionals throughout Canada. The first of those two courses, which is the longest running, is titled "Physical Principles of Hydrology" and is typically held in the Kananaskis Valley in the province of Alberta. The 10-day long university-accredited field course notably examines the physical principles and processes that govern hydrology, with a special focus on Canadian conditions. The second course, titled "Principles of Hydrologic Modelling", is also an annual, university-accredited course aimed at graduate students and professionals that debuted in 2017. Its focus is on all the development stages of computational models of watershed hydrology, including model output interpretation and uncertainty assessment in the context of scientific investigation and water resource management in alpine, forest, prairie and agricultural settings.

International Course on Regional Strategies for the Management of Transboundary Aquifers. UNAM, Mexico City, Mexico (August 2017). This UNESCO IHP sponsored program examined public policy for the management of transboundary aquifers using Mexico as a model. Based on the international instruments developed for this purpose and considering the asymmetries that characterize the management of transboundary groundwater between Mexicoand the United States, this course examined approaches for the joint management of international watercourses and means to protect and conserve this water, using based on principles of sovereignty, territorial integrity, and sustainable development.

Still with respect to training, a bottom-up initiative spearheaded by the CGU and worth mentioning was launched in 2016 with the acronym "LUGNuts", which stands for "Linked UnderGraduate experiments on Nutrients". This initiative was first launched to address the fact that opportunities for collaborative, interdisciplinary research tackling complex environmental problems are often much less available for undergraduate students. The goal of this initiative is, therefore, to create a network of Honours thesis students who tackle the same research questions at different study sites across Canada and, if possible, in the United States as well with partner American universities. In the first year of this initiative, undergraduate students from Wilfrid Laurier University, the University of Winnipeg, the University of Saskatchewan and the University of Missouri conducted a range of lab experiments to examine the impact of freeze- thaw cycles on nutrient release from riparian and wetland vegetation. Collaborative work was instigated early in the undergraduate students by organizing biweekly videoconferences during which they worked together to design their protocols, decide on a template for data sharing and analysis, and draft their literature review. At the end of the year, all the students involved wrote an individual Honours thesis but also contributed data and expertise to a common manuscript meant to summarize results across sites. The success of the LUGNuts initiative in its first year has led to a second and a third edition, with different sets of Honours thesis students working on different topics from one year to the next.

Lastly, through its Hydrology Section, CGU is particularly committed to creating opportunities for undergraduate and graduate students to establish their professional network and benefit for career advice and mentorship, this through various activities. One example of activity is the yearly sponsorship of annual student meetings. University departments are encouraged to host those student conferences – with costs partly reimbursed by the Hydrology Section – and the aim is for two annual student conferences to be held each year, i.e., one in Western Canada and one in Eastern Canada. Those day-long student conferences are usually very well attended (e.g., ~100 attendees at the 2017 Eastern conference at the University of Guelph, with 30 oral presentations and 22 poster presentations) and really foster a sense of community among the students. Otherwise, since 2016 a significant number of networking activities have been led by the Canadian Young Hydrologic Society (CYHS) with the financial support of the CGU Hydrology Section. CYHS is the Canadian branch of the Young Hydrologic Society (YHS), which is an international initiative focused on enhancing interactions between young hydrologists through activities ranging from pop-up sessions at large conferences to seminars and social nights. However, despite its affiliation with YHS, the CYHS does operate independently from the international society. At the last three CGU annual meetings, the CYHS notably organized workshops on different themes, from "Challenges and opportunities in Canadian hydrology" (2016) to "Progression of a scientific career in academia" (2017), "Careers in hydrology: Options and insights" (2018) and "Tips and Tricks for publishing in hydrology" (2018). Those workshops – which are always book-ended by "pub nights – have truly fulfilled a need in the young Canadian hydrology community, as evidenced by the steady level of attendance from year to year (> 50 early-career attendees + other attendees, for a total of 75 to 100 participants). The CYHS has a strong social media presence (i.e., Twitter, Facebook) and its increasing level of involvement in the active building of the Canadian hydrologic community has led to it becoming an official committee of the CGU - Hydrology Section.

3.5) Select national and international advisory efforts

The Canadian Hydrological community is involved in many national and international projects in an advisory role. Some examples of such projects are listed below.

- Geological Survey of Canada (GSC): Through its Groundwater Geosciences Program, the GSC recently re-connected with the International Groundwater Resources Assessment Centre (IGRAC) to advance the connection between the Canadian

Groundwater Information Network (GIN) and the Global Groundwater Information System of IGRAC.

- UNESCO Chair in Global Environmental Changes: The chair held by Yves Prairie at the University of Quebec, Montreal, Canada was involved in developing the G-res tool launched in Addis Ababa in 2017. The tool builds on a conceptual framework developed by researchers from the University of Québec at Montreal (UQÀM), the Norwegian Foundation for Scientific and Industrial Research (SINTEF) and the Natural Resources Institute of Finland (LUKE) for measuring the carbon footprint of hydropower reservoirs (https://www.hydropower.org/news/g-res-new-tool-for-measuring-carbon-footprint-of-reservoirs).

- Canadian Biosphere Reserves Association (CBRA): the CBRA represents Canadian Biosphere Reserves at the Steering Committee of EuroMAB, which is the sub-network that represents European and North American Biosphere Reserves.

- Man and the Biosphere (MAB) Programme: Canada continues to contribute to this programme through its 18 Biosphere Reserve sites (two new sites were added in 2016). These Biosphere Reserves are located in 8 provinces and 1 territory and cover a wide spectrum of Canada's diversity. The Canadian Biosphere Reserves Association (CBRA) supports the Canadian Biosphere Reserves in the achievement of their mandates and to demonstrate their collective value nationally and internationally.

4) Major publications

Canadians involved in IAHS-related research were very productive in 2014-2018. To truly capture the breadth of research being done in the country, the evaluation of the Canada-wide publication record was not based on active CGU, CWRA, CMOS and CCIAH members only but rather included all scientists affiliated with a Canadian institution, organization or company. A cursory search through ISI Web of Science revealed that between January 2014 and December 2018, well over 2500 peer-reviewed papers co-authored by at least one Canada-based scientist were published on topics related to the hydrology, biogeochemistry or geomorphology of freshwater systems or landscapes. The number of papers published in some well-known journals such as the *Journal of Hydrology*, *Hydrological Processes* or *Water Resources Research* was very high (Figure 2). It should also be noted that some Canadian scientists demonstrated their impact in the field either through articles published in prestigious journals such as *Nature* journals, or through their crafting of literature reviews published in journals that require authors to synthesize the state-of-the-art and offer new directions for the future (e.g., *Earth-Science Reviews*, *Wiley Interdisciplinary Reviews-Water*, see Figure 2).

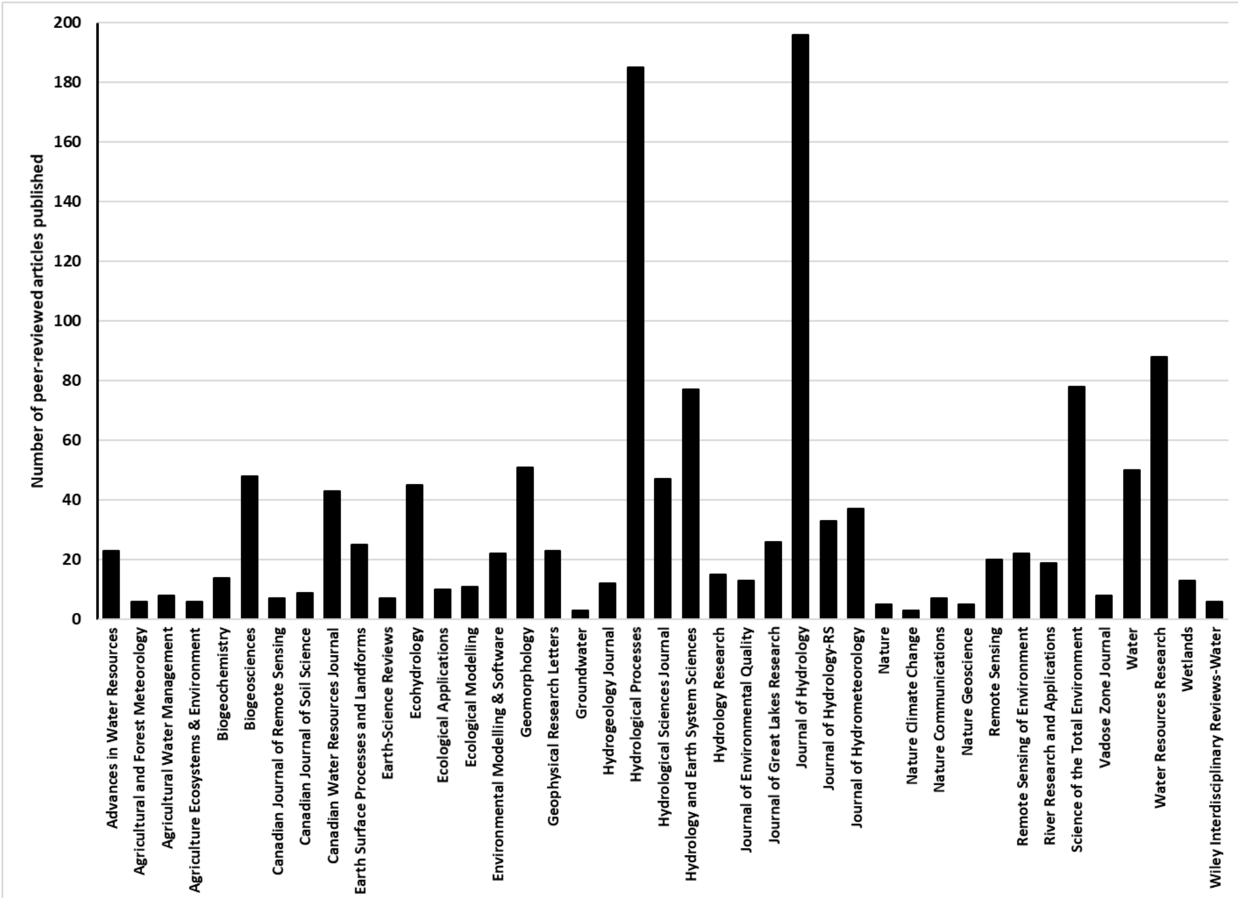

Figure 2. Peer-reviewed publications aligned with the IAHS mandate and published by Canadian scientists in select journal between 2014 and 2018 (based on data available through ISI Web of Science).

It should also be noted that each year, in collaboration with the journal *Hydrological Processes*, the president and the vice-president of the CGU Hydrology Section serve as guest editors for a special issue of selected papers that were presented at CGU annual meetings. Those papers usually cover highly varied topics which are quickly introduced and summarized in a special issue preface written by the guest editors. For the years 2014, 2015, 2016, 2017 and 2018, respectively 15, 22, 11, 7 and 8 peer-reviewed papers were included in the CGU – Hydrology Section special issue of *Hydrological Processes*. More information about the individual papers included in the special issues can be found on the website of *Hydrological Processes* (https://onlinelibrary.wiley.com/journal/10991085).

5) International science meetings hosted or attended by Canadian scientists.

5.1) Meetings hosted by Canada (in 2018)

- Canada hosted the 8th open science meeting of the Global Energy and Water Exchanges (GEWEX) Project of the World Climate Research Programme (WCRP) in Canmore, AB, Canada on 6–11 May, 2018. The meeting was titled "Extremes and Water on the Edge" and it focused on extreme events and the changing water cycle, including presentations and discussions on issues ranging from mountain and high latitude hydrology to atmospheric and land modeling and observations. It was attended by approximately 360 scientists from over 40 countries around the world, and was considered the premiere scientific event of the year for WCRP regarding climate and water. More information ca be found at https://www.gewexevents.org/events/2018conference/

- The First International Conference on Water Security was held in Toronto on June 17-20, 2018. During this conference, the International Hydrological Programme (IHP) held a session on Water Security with the involvement of relevant UNESCO Category 2 Centres and Chairs (https://en.unesco.org/events/first-international-conference-water-security).

5.2) Participation in meetings abroad (IAHS and UN-related conferences)

- G-Wadi Global Conference, "G-WADI more than a decade enhancing water and sustainable development for arid regions", Beijing, P.R.C., October 25-27, 2016. http://www.asian-gwadi.org/global-conference-g-wadi-more-than-a-decade-enhancing-water-and-sustainable-development-for-arid-regions/

- There was Canadian participation at the conference "Water Security in Human Settlements: Responses to Water Scarcity", held in Tehran, Iran, May 2017.

- Shared Water of North America, Special Session of the XVI World Water Congress, Cancun, Mexico, May, 2017.

- "Water resources management and the competition/balance between humans and ecosystems (eco-hydrology)" session at the IAHS Scientific Assembly 2017, 10–14 July 2017, Port Elizabeth, South Africa.

- UNESCO Knowledge Forum on Water Security and Climate Change: Innovative Solutions for Sustainable Water Resources Management, Paris, October 18, 2017. He presented: "The Global Water Futures Programme and its Science Contributions to the UN's Sustainable Development Goals and the Paris Climate Agreement", and "Climate Change and Mountain Hydrology: Results from the Global Energy and Water Exchange Project's International Network for Alpine Research Catchment Hydrology."

- Environment and Climate Change Canada (ECCC) participated in 8th World Water Forum (WWF-8), held in Brasilia, Brazil, March 18-23, 2018. Canada contributed to two special sessions: (i) National hydrological networks in continental sized countries – past, present and future, problems and perspectives, and (ii) National water quality networks in continental sized countries - past, present and future, problems and perspectives.

6) Major awards received by Canadian scientists

The CGU awards three Union-level awards annually, namely the internationally recognized J. Tuzo Wilson Medal, the Young Scientist Award and the Meritorious Service Award. While nomination for those awards come from all sections of the CGU, members affiliated with the Hydrology, Biogeosciences and Earth Surface Processes Sections and whose research is aligned with the mandate of the IAHS have been especially successful at getting Union-level awards between 2014 and 2018. For instance, the J. Tuzo Wilson Medal is awarded to geoscientists in recognition of their outstanding contributions to the advancement of knowledge in any research area of the CGU, and evaluation criteria include excellence in scientific or technical research, instrument development, industrial applications and teaching. Two recent recipients of the Tuzo Wilson Medal are affiliated with the CGU Hydrology Section, namely Philip Marsh (2014) and John Pomeroy (2017). As for the Young Scientist Award, it is given in recognition of outstanding research contributions – in terms of quality and impact – by an early-career geoscientist. Four of the five most recent winners of the CGU Young Scientist Award were affiliated with the Hydrology and Biogeosciences Sections at the time of award announcement, namely Genevieve Ali (2014), Jeffrey McKenzie (2015), Scott Jasechko (2016) and Carl Mitchell (2017).

Beyond those CGU awards, Canadian hydrologists, biogeochemists and geomorphologists have also been successful at obtaining major national and international awards in the 2014-2018 period, notably:

- Recognition as a conferred fellow of the International Union of Geodesy and Geophysics (IUGG) and its Associations: Gordon Young (Hydrology, 2015)
- Recognition as a fellow of the American Geophysical Union: Michael Church (Earth Surface Processes, 2015), Barbara Sherwood Lollar (Hydrology, 2015)
- Election as a fellow of the Royal Society of Canada (i.e., Canada's National Academy of Science): Nigel Roulet (Hydrology, 2014), Philippe van Cappellen (Hydrology, 2015), Jeffrey McDonnell (Hydrology, 2015), David Blowes (Hydrology?, 2017), John Pomeroy (Hydrology, 2018), Howard Wheater (Hydrology, 2018)
- Dooge Medal of the International Hydrology Prize of IAHS/WMO/UNESCO: Jeffrey McDonnell (Hydrology, 2016), Howard Wheater (Hydrology, 2018)
- AGU Early Career Hydrologic Science Award: Thomas Gleeson (Hydrology, 2015)
- Soil Science Society of America Soil Physics and Hydrology Early Career Award: Asim Biswas (2016, Hydrology)
- Journal of Great Lakes Research/Elsevier Early Career Scientist Award: Christopher Wellen (2015, Hydrology and Biogeosciences)
- CMOS President's Prize: *Damon Matthews (2015)* for his meritorious paper (co-authored with Caldeira) entitled “Stabilizing climate requires near-zero emissions” published in Geophysical Research Letters in 2008.
- CMOS Andrew Thomson Prize in Applied Meteorology: *Diana Verseghy (2015)* for her outstanding career-long contributions to develop a land-surface scheme for climate and weather models
- CMOS Andrew Thomson Prize in Applied Meteorology: *René Laprise (2016)* for his long-standing leadership and contributions to the development of regional climate modelling.
- CMOS President's Prize: *Patrick Cummins, Diane Masson (2017)* jointly for their 2014 paper “Climatic variability and trends in the surface waters of coastal British Columbia” published in *Progress in Oceanography* . This paper shows how variability in surface properties is related to the influence of freshwater discharge and wind stress, and that statistically significant warming trends are emerging.

- CMOS Andrew Thomson Prize in Applied Meteorology: E. Ray Garnett (2017) for his long and dedicated service in the development and interpretation of climatological products for the agricultural sector.
- CMOS President's Prize: Kirsten Zickfeld (2018) for her 2009 paper "Setting cumulative emissions targets to reduce the risk of dangerous climate change," published in the Proceedings of the National Academy of Sciences. Dr. Zickfeld's paper was the first to propose that international climate policy targets aimed at avoiding "dangerous anthropogenic interference" could be based on limiting cumulative carbon emissions, and continues to be highly cited.
- CMOS Andrew Thomson Prize in Applied Meteorology: *Alex J. Cannon (2018)* for his important contributions to the understanding of our surface hydrology and climatic extremes in Canada, and how they might change in the future, for his application of Artificial Intelligence methods to meteorological and climatological problems, and for his unselfish dedication to making his software tools freely available to the scientific community.

7) Other major achievements

7.1 Completed and ongoing scientific projects

- At the University of Saskatchewan's **Global Institute for Water Security (GIWS)**, sustainable use of the world's water resources and protection against natural hazards such as flood and drought are key priorities. GIWS is co-located with Environment Canada's National Hydrology Research Centre at Innovation Place and funded through the **Canada Excellence Research Chair in Water Security (CERC)**, a $30-million, joint federal-provincial-university commitment over seven years. GIWS is developing the modelling tools, techniques and policies to sustainably manage the world's freshwater resources. (https://www.usask.ca/water/)

- The **CERC/GIWS** has successfully established the following large-scale observatories and major facilities of national and international significance:
  - Saskatchewan River Basin (410,000 km^2; includes research sites in the Rocky Mountains, Boreal Forests, Prairies and the Saskatchewan River Delta)
  - Mackenzie River Basin (1.8 million km^2)
  - Smart Water Systems Laboratory
  - Mine Overlay Site Testing Facility
  - The Ultrahigh Resolution Mass Spectrometer Facility

- **Global Water Futures: Solutions to Water Threats in an Era of Global Change** is a University of Saskatchewan-led research program that is funded in part by a $77.8-million grant from the Canada First Research Excellence Fund. The overarching goal of the program is to deliver risk management solutions – informed by leading-edge water science and supported by innovative decision-making tools – to manage water futures in Canada and other cold regions where global warming is changing landscapes, ecosystems, and the water environment. Global Water Futures (GWF) aims to position Canada as a global leader in water science for cold regions and will address the strategic needs of the Canadian economy in adapting to change and managing risks of uncertain water futures and extreme events (https://gwf.usask.ca/)

  - GWF funded 21 projects (94 researchers from 10 Canadian universities, 37 partners including international institutions, government agencies, industry partners, non-governmental organizations, and Indigenous communities) to address two key areas: transformative science to help us understand, diagnose and predict change, and developing new decision support systems using new sensors, analytical procedures, and computer models. These projects will contribute to a better understanding of snow and rain storms, floods and droughts, how to better measure and manage the quality of source waters, how deep groundwater is affected by the surface, how to improve water governance and even how to encourage global water citizenship (https://gwf.usask.ca/science/pillar-1-2-projects.php).
  - GWF also funded 12 large pan-Canada user/stakeholder-led research projects (117 researchers from 15 Canadian universities, 135 partners including international institutions, government agencies, industry partners, non-governmental organizations, and Indigenous communities) that are looking at protecting prairie agricultural lands from drought and floods, mitigating algae blooms in lakes, developing new monitoring systems for Canadian watersheds using drones and satellites, using environmental DNA to assess ecosystem health, understanding the impact that changes to mountain snow packs and glaciers will have on drinking water, and co-create Indigenous water-quality tools with First Nations (https://gwf.usask.ca/science/pillar-3-projects.php).

- The **Changing Cold Regions Network (CCRN)** is a Canadian network that concluded at the end of March 2018 and which aimed to understand, diagnose and predict interactions amongst the cryospheric, ecological, hydrological and climatic components of the changing Earth system at multiple scales with a geographical focus on Western Canada. CCRN has successfully reached the end of its five-year programme (2013–2018), and as a network, CCRN made major advancements (i) towards improving our understanding of recent Earth system change in the cold interior of western and northern Canada, (ii) advancing water, weather, climate and environmental prediction, and (iii) improving our understanding of Earth system processes and their representation in hydrological, atmospheric and ecological models. CCRN was led by Professor Howard Wheater at the University of Saskatchewan, and included a team of over 40 research scientists from eight Canadian universities and four federal government agencies, as well as over a dozen key international collaborators. The network has produced invaluable scientific and technical advancements that build upon many previous research initiatives in western Canada and with global applicability for cold regions in general, and helped place Canada as a leader in cold regions hydrology and hydro-meteorology. More information on the network, its achievements, and access to its data and publications can be found at http://ccrnetwork.ca.

- The **International Network for Alpine Research Catchment Hydrology (INARCH)** is a crosscutting project of the GEWEX Hydroclimatology Panel (GHP) and links strongly to UNESCO's IHP. Its objectives are to better understand alpine cold regions hydrological processes, improve their prediction, diagnose their sensitivities to global change and find consistent measurement strategies. INARCH maintains a global network of instrumented mountain research basins and includes 46 participants and many other collaborators from across the world, many of whom are leading scientists in the fields of mountain hydrology, atmospheric science, glaciology, modelling, and other related disciplines. This network has led many important advancements in mountain water and climate science, particularly around the topics of mountain meteorological measurement standardization, understanding changing atmospheric dynamics, improving physical process representation, downscaling, and data assimilation in numerical models, examining the global validity of various model routines for mountain, and exploring the effects of transient landscape and ecosystem changes, and their representation in models. The group recently met for their third annual workshop, 8–9 February, 2018, in Germany. Detailed information can be found at http://www.usask.ca/inarch.

- The **Canada Water Network (CWN)**, headquartered at the University of Waterloo, Ontario, is a national Network of Centres of Excellence focused on research and knowledge mobilization on three core water management challenges: protecting public health, protecting watersheds and ecosystems, and ensuring sustainable water infrastructure. The CWN continues to use a collaborative consortium-based approach to focus research and knowledge mobilization activities to address broad national issues prioritized by collective public and private sector end users. More information on the CWN, it projects, and access to annual reports can be accessed at http://www.cwn-rce.ca/.

- The **Arctic Monitoring and Assessment Programme (AMAP)**, an Arctic Council Working Group, has the purpose to provide reliable and sufficient information on the status of, and threats to, the Arctic environment, and provide scientific advice on actions to be taken in order to support Arctic governments in their efforts to take remedial and preventive actions relating to contaminants and adverse effects of climate change. Canada continues to contribute to AMAP initiatives – for example a chapter on "Freshwater" in the AMAP assessment "Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017). More information on AMAP and its initiatives can be found at https://www.amap.no/.

- The **Conservation of Arctic Flora and Fauna (CAFF)** is the biodiversity working group of the Arctic Council. Under the auspices of CAFF is the **Circumpolar Biodiversity Monitoring Program (CBMP)** which comprises an international network of scientists, governments, Indigenous organizations and conservation groups working to harmonize and integrate efforts to monitor the Arctic's living resources. Canada continues to contribute to CAFF co-leading with Sweden the Freshwater Expert Monitoring Group (FEMG) of the Circumpolar Biodiversity Monitoring Program (CBMP) and development of a circumpolar monitoring network/program. More information on CAFF and the CBMP can be found at https://www.caff.is/.

- **ArcticNet** is a Network of Centres of Excellence (NCE) of Canada that brings together scientists and managers in the natural, human health and social sciences with their partners in Inuit organizations, northern communities, federal and provincial agencies and the private sector to study the impacts of climate change in the coastal Canadian Arctic. Over 150 ArcticNet researchers and 1000 graduate students, postdoctoral fellows, research associates, technicians and other specialists from 34 Canadian universities, and 20 federal and provincial agencies and departments collaborate with more than 150 partner organizations in 14 countries. ArcticNet offers a unique multi-disciplinary and cross-sectorial environment to train the next generation of specialists, from north and south, needed to manage the Canadian Arctic of tomorrow. For more information on ArcticNet, please visit http://www.arcticnet.ulaval.ca/.

- **Environment and Climate Change Canada (ECCC)** is Canada's lead federal department for a wide range of environmental issues, including those related to water, and the potential impacts of a changing climate. ECCC conducts regional and national operational monitoring programs and supporting scientific investigations on water quantity (Meteorological Service Canada – Water Survey of Canada Program) and water quality (Water Quality Monitoring and Surveillance – Water Sciences and Technology Directorate). The Water Survey of Canada (WSC) is the national authority responsible for the collection, interpretation and dissemination of standardized water resource data and information in Canada. ECCC is Canada's lead department in freshwater research, focusing on the generation of new scientific knowledge needed to sustain Canada's water resources and freshwater ecosystems. For more information, please see http://ec.gc.ca.

- Under **Natural Resources Canada (NRCan)**, the **Geological Survey of Canada (GSC)** through their **Groundwater Geosciences Program** assesses Canada's key aquifer systems and makes the data available through a national groundwater portal (the Groundwater Information Network (GIN)) that links several databases to provide baseline information useful to stakeholders (government, private sector, industry, water management agencies, and well owners) in their decision-making process. The data from the assessment activities are made available through the GIN. The GIN aims to improve knowledge of groundwater systems and enhance groundwater management through increased access to groundwater information. It connects databases from NRCan's key aquifer information and several provinces and territories. For more information on NRCan's groundwater program, and access to numerous reports and publications, please visit http://www.nrcan.gc.ca/earth-sciences/resources/federal-programs/groundwater-geoscience-program/10909.

- **Agriculture and Agri-food Canada (AAFC)** continues its national roles for environmental and water management programming related to Canadian agriculture and water. Some of their key programs and support related to agriculture and water include: Canadian Agricultural Adaptation Program; Drought Watch; Geospatial Products Program to view such things as drought conditions, soil type; Agricultural Pest Management; etc. More information on AAFC and its programs can be found at http://www.agr.gc.ca.

- The **International Joint Commission (IJC)** is a binational institution established under the 1909 Boundary Waters Treaty to help prevent and resolve disputes between the United States of America and Canada. The IJC continues to act as an independent and objective advisor to the two governments, pursuing the common good of both countries. For more information about the IJC and its mission, mandates, and activities, please visit http://www.ijc.org/en_/.

- The **Canadian Oil Sands Innovation Alliance (COSIA)** is a partnership between universities and industry. One of the main foci of the alliance is the management of water during the industrial phase as well as reclamation. COSIA acts to advance theories, technologies and approaches to efficient water use that informs policy not only for this industry, but will be applicable to all large scale natural resource extraction. For more information on COSIA, please visit https://www.cosia.ca/.

7.2 Institutional relations/cooperation

Some large-scale initiatives that fostered institutional relations and cooperation in the 2014-2018 period are listed below.

- The **Global Institute for Water Security (GIWS)**, University of Saskatchewan (UofS) is the host of the World Climate Research Programme's (WCRP) only Regional Hydroclimate Project in North America – Changing Cold Regions Network (CCRN) and also hosts the WCRP's Global Hydroclimate Project & UNESCO's International Hydrological Programme - International Network for Alpine Research Catchment Hydrology (INARCH). In addition, GIWS is the Canadian node for the Sustainable Water Futures Programme with the Future Earth. Recently, GIWS-UofS has been included as a new member with the University Consortia for Atmospheric Research (UCAR).

- The following professional development activities were established by the **Global Institute for Water Security (GIWS)** to provide graduate students and postdoctoral fellows with skills for their career development: 1) An annual short course for doctoral students and postdoctoral fellows "Launching an Academic Career" by creating their own research brand and orchestrating a power research group; 2) "Post Doc Mentoring Lunch" where GIWS faculty actively address mentorship issues, 3) The GIWS Distinguished Lecture Series, "Breakthroughs in Water Security Research" brings 11 international world-leading scientists to Saskatoon each Fall for lectures, tutorials and workshops.

- The University of Waterloo established the **Water Institute** in 2009, building on four decades of excellence in water-related research, education and innovation. Recognizing the collective excellence of water research programs at the University of Waterloo, the Water Institute was formed to coordinate and support the extensive group of university researchers, staff, students and partners, and to bring them together within a single institutional setting and foster national and international collaborations and water related initiatives. The graduate Collaborate Water Program is a flagship example in Canada, and around the world, of a truly interdisciplinary water graduate program.

8) Concluding statement

The list of activities included in the present report, even though incomplete due to space and time constraints, showcases the significant contributions made by the Canadian community to hydrological sciences. Those contributions not only provide tangible evidence of the breadth of expertise covered by Canadian hydrologists, hydrogeologists, biogeochemists and geomorphologists but also serve as a great outlook to the future: young and emerging Canadian scientists are, today, in a unique position to become exposed to all that expertise and benefit from superior training. It should, however, be noted that in a manner not dissimilar to other Canadian geoscientists, the success of Canadian hydrologists, hydrogeologists, biogeochemists and geomorphologists in producing new knowledge and training the new generation is intimately linked to funding. Indeed, the limiting factor to post-graduate training in hydrological sciences is not the lack of will but rather a difficulty to obtain funds: the access to scholarships for students is highly variable from province to province. NSERC CREATE grants have helped alleviate that burden a bit, with over CAD $3,000,000 awarded to IAHS-related research over the 2014-2018 period (and more funding awarded to other water scientists). Enhancing research-industry collaborations is critical and has been supported by several NSERC-led initiatives, in particular. For example, CGU members whose research aligns with the IAHS mandate have been successful at establishing research-industry collaborations over the past five years, through short-term projects (e.g., 6-month long NSERC Engage Grants, approximate funding total of CAD $1,000,000 over the 2014-2018 period), medium-term projects (e.g., 3-year long NSERC CRD grants, approximate funding total of CAD $6,900,000 over the 2014-2018 period), and longer-term endeavours (e.g., NSERC IRCs, approximate funding total of CAD $920,000 over the 2014-2018 period). NSERC Strategic Partnership Grants (SPG), which required academic researchers to partner up with at least one supporting, non-academic organization to tackle early-stage project research in a government-identified target area, have also helped carry IAHS-related research in Canada, with CAD 4,500,000 of funds managed by CGU members between 2014 and 2018, and the same amount of funds managed by water researchers affiliated with sister organizations to the CGU (e.g., CWRA, in particular). There is still a great need for pure, experimental or "discovery" science, though: such "discovery" science is mostly covered through individual NSERC Discovery grants which are not large funding envelopes (i.e., average grant of CAD $26,556 per year for early-career geoscientists and CAD $36,781 per year for established geoscientists based on the 2017 competition results). The availability of funding for environmental research is also strongly tied to provincial and federal politics, with both major and ad-hoc programs susceptible to being created, revamped or suspended at any point in time. While this has not been emphasized in the present report, many CGU, CWRA, CMOS and CCIAH members working on IAHS-related research are actively involved in policy work, advisory councils, science communication and outreach, etc. in Canada, the United States, Europe and Asia and they strive to convince stakeholders of the importance of high-quality research infrastructure, high-quality data and high-quality personnel in order to ensure a sustainable future and support science-driven political agendas. It is the hope of the community that solid discovery research, coupled with better science communication and small incremental efforts at the science-policy-practice interface will lead to an acknowledgment of the importance of supporting hydrological sciences through substantial – and more importantly temporally stable – funding programs.

Appendix A
Canadians involved in IAHS-related activities (according to 2018 data only)

Affiliation	Last name	First name	Status	CGU Section
Agriculture and Agri-Food Canada	Schneider	Kimberley	Regular	Biogeosciences
Agriculture and Agri-Food Canada	Wilson	Henry	Regular	Biogeosciences
APEGA	Sneddon	Tom	Regular	Hydrology
Aquanty Inc	Boluwade	Alaba	Regular	Hydrology
Associated Engineering	Fyke	Jeremy	Regular	Earth Surface Processes
BC Hydro	Jasek	Martin	Regular	Hydrology
BC Min Forests, Lands and Natural Resource Ops	Spittlehouse	Dave	Regular	Biogeosciences
Brandon University	Golubev	Vitaly	Student	Hydrology
Brandon University	Whittington	Pete	Regular	Hydrology
Brock University	Pisaric	Michael	Regular	Earth Surface Processes
Can. Com. on River Ice Pro & Environment	Morse	Brian	Regular	Hydrology
Canadian Forest Service	Webster	Kara	Regular	Biogeosciences
Canadian Hydrographic Service	Laing	Janelle	Regular	Hydrology
CANQUA	Ward	Brent	Regular	Earth Surface Processes
Capital Region District	Gardner	Tobi	Regular	Hydrology
Carleton University	Burn	Christopher	Regular	Earth Surface Processes
Carleton University	Mueller	Derek	Regular	Earth Surface Processes
Carleton University	Palmer	Mike	Student	Biogeosciences
CCCma	Sun	Shanshan	Regular	Earth Surface Processes
China University of Geosciences(Beijing)	Wu	Pan	Student	Hydrology
City of Delta	Howie	Sarah	Regular	Hydrology
Clarkson University	Knack	Ian	Regular	Hydrology
Clarkson University	Smith	Tyler	Regular	Hydrology
Concordia University	Sklar	Leonard	Regular	Earth Surface Processes
Concordia University	Hatami	Shadi	Student	Hydrology
Concordia University	Zaerpour	Masoud	Student	Hydrology
Consulting Geoscience	Ellis	Erica	Regular	Earth Surface Processes
Cornell University	Goud	Ellie	Student	Biogeosciences
CSIR- National Institute of Oceanography	Prasad	Pankaj	Student	Earth Surface Processes
Dalhousie Unviersity	Kurylyk	Barret	Regular	Hydrology
Environment and Climate Change Canada	Bartlett	Paul	Regular	Hydrology
Environment and Climate Change Canada	Elliott	Jane	Regular	Biogeosciences
Environment and Climate Change Canada	Seglenieks	Frank	Regular	Hydrology
Environment and Climate Change Canada	Spence	Chris	Regular	Hydrology
Geological Survey of Canada	Morse	Peter	Regular	Hydrology
Global Institute of Water Security	Gharari	Shervan	Regular	Hydrology
Global Institute for Water Security	Haghnegahdar	Amin	Regular	Hydrology
Global Institute for Water Security	Wong	Jefferson	Regular	Hydrology
Government of Alberta	Mallon	Christopher	Regular	Earth Surface Processes
Hilcon Limited	BURRELL	BRIAN	Regular	Hydrology
IIESTS	Mishra	Ravi	Student	Earth Surface Processes
Indian Institute of Technology Roorkee	Taxak	Arun Kumar	Student	Hydrology
Manitoba Hydro	Morris	Michael	Regular	Hydrology
McElhanney Consulting Services	Miller	Courtney	Regular	Biogeosciences

Affiliation	Last name	First name	Status	CGU Section
McGill University	Douglas	Peter	Regular	Biogeosciences
McGill University	McKenzie	Jeffrey	Regular	Hydrology
McGill University	Moore	Tim	Regular	Biogeosciences
McGill University	Rainville	Luc	Regular	Earth Surface Processes
McGill University	Lyon	Laura	Student	Hydrology
McGill University	Rankin	Tracy	Student	Biogeosciences
McGill University	Sadler	Morgan	Student	Hydrology
McGill University	Somers	Lauren	Student	Hydrology
McGill University	Vidana Gamage	Duminda	Student	Hydrology
McMaster University	Arain	M. Altaf	Regular	Biogeosciences
McMaster University	Carey	Sean	Regular	Hydrology
McMaster University	Harris	Lorna	Regular	Biogeosciences
McMaster University	Irvine	Sarah	Regular	Biogeosciences
McMaster University	Thorne	Robin	Regular	Hydrology
McMaster University	Waddington	James Michael	Regular	Hydrology
McMaster University	Woo	Ming-ko	Regular	Hydrology
McMaster University	Xu	Bing	Regular	Biogeosciences
McMaster University	Beamesderfer	Eric	Student	Biogeosciences
McMaster University	Biagi	Kelly	Student	Hydrology
McMaster University	Furukawa	Alex	Student	Hydrology
McMaster University	McKenzie	Shawn	Student	Biogeosciences
McMaster University	Nicholls	Erin	Student	Hydrology
McMaster University	Sauer	Stefan	Student	Hydrology
McMaster University	Shatilla	Nadine	Student	Hydrology
McMaster University	Singh	Supriya	Student	Hydrology
McMaster University	Tang	Weigang	Student	Hydrology
McMaster University	Wilkinson	Sophie	Student	Hydrology
Memorial University of Newfoundland	Galagedara	Lakshman	Regular	Hydrology
Mount Allison University	Ollerhead	Jeff	Regular	Earth Surface Processes
Ontario Power Generation	Kornelsen	Kurt	Regular	Hydrology
Queen's University	Lamoureux	Scott	Regular	Earth Surface Processes
Queen's University	Chu	Lianne	Student	Hydrology
Queen's University	Hung	Jacqueline	Student	Biogeosciences
Queen's University	Thiel	Gillian	Student	Biogeosciences
Ryerson University	Oswald	Claire	Regular	Hydrology
Ryerson University	Wellen	Christopher	Regular	Biogeosciences
Ryerson University	Siebert	Krystal	Student	Hydrology
Simon Fraser University	Clague	John	Regular	Earth Surface Processes
Simon Fraser University	Leach	Jason	Regular	Hydrology
Simon Fraser University	Dinney	Meaghan	Student	Earth Surface Processes
Simon Fraser University	Gingerich	Travis	Student	Earth Surface Processes
Simon Fraser University	Mackie	Kirsty	Student	Earth Surface Processes
Simon Fraser University	Nzotungicimpaye	Claude-Michel	Student	Biogeosciences
Stanford University	Ward	Ellen	Student	Hydrology
Syracuse University	Kelleher	Christa	Regular	Hydrology
Syracuse University	Lautz	Laura	Regular	Hydrology
Syracuse University	Russoniello	Christopher	Regular	Hydrology
Syracuse University	Gutchess	Kristina	Student	Hydrology

Affiliation	Last name	First name	Status	CGU Section
Trent University	Cooke	Ciara	Student	Hydrology
TROUT Hydrography Inc.	West	Doug	Regular	Hydrology
University of Northern British Columbia	Dery	Stephen	Regular	Hydrology
University of Northern British Columbia	Mortezapour	Marzieh	Student	Earth Surface Processes
Université de Moncton	El-Jabi	Nassir	Regular	Hydrology
Universite de Montreal	Franssen	Jan	Regular	Earth Surface Processes
Université de Sherbrooke	Bahrami	Ala	Student	Hydrology
Université Laurentienne	Watelet	Anne	Regular	Hydrology
Université Laval	Brummell	Martin	Regular	Biogeosciences
Université Laval	Isabelle	Pierre-Erik	Student	Hydrology
University of Alaska Fairbanks	Hinzman	Larry	Regular	Hydrology
University of Alberta	Faramarzi	Monireh	Regular	Hydrology
University of Alberta	Olefeldt	David	Regular	Biogeosciences
University of Alberta	Reyes	Alberto	Regular	Earth Surface Processes
University of Alberta	Sedaei	Nazila	Regular	Hydrology
University of Alberta	Sharp	Martin	Regular	Hydrology
University of British Columbia Okanagan	Bauer	Bernard	Regular	Earth Surface Processes
University of British Columbia	Church	Michael	Regular	Earth Surface Processes
University of British Columbia	Clarke	Garry	Regular	Hydrology
University of British Columbia	McDougall	Scott	Regular	Earth Surface Processes
University of British Columbia	Moore	Dan	Regular	Hydrology
University of British Columbia	Exler	Johannes	Student	Hydrology
University of British Columbia	Gronsdahl	Stefan	Student	Hydrology
University of British Columbia, Okanagan	Li	Qiang	Student	Hydrology
University of British Columbia	Szeitz	Andras	Student	Hydrology
University of British Columbia	Vickerman	William	Student	Hydrology
University of Calgary	Cey	Edwin	Regular	Hydrology
University of Calgary	Hallett	Douglas	Regular	Biogeosciences
University of Calgary	Hayashi	Masaki	Regular	Hydrology
University of Guelph	Ambadan Thomas	Jaison	Regular	Hydrology
University of Guelph	Berg	Aaron	Regular	Hydrology
University of Guelph	Cockburn	Jaclyn	Regular	Earth Surface Processes
University of Guelph	Donald	John	Regular	Hydrology
University of Guelph	Manns	Hida	Regular	Hydrology
University of Guelph	Lapierre	Jared	Student	Biogeosciences
University of Guelph	Miller	Bryce	Student	Earth Surface Processes
University of Guelph	Pardo Lara	Renato	Student	Hydrology
University of Hohenheim	Weber	Tobias	Regular	Hydrology
University of Manitoba	Ali	Genevieve	Regular	Hydrology
University of Manitoba	Clark	Shawn	Regular	Hydrology
University of Manitoba	Bansah	Samuel	Student	Hydrology
University of Manitoba	Haque	Md Aminul	Student	Hydrology
University of Manitoba	Holmes	Tegan	Student	Hydrology
University of Manitoba	Ross	Cody	Student	Hydrology
University of Melbourne	Russell	Kathryn	Student	Earth Surface Processes
University of Regina	Hall	Britt	Regular	Biogeosciences
University of Regina	Sauchyn	Dave	Regular	Hydrology

Affiliation	Last name	First name	Status	CGU Section
University of Saskatchewan	De Boer	Dirk	Regular	Hydrology
University of Saskatchewan	Harder	Phillip	Regular	Hydrology
University of Saskatchewan	Ireson	Andrew	Regular	Hydrology
University of Saskatchewan	Kinar	Nicholas	Regular	Hydrology
University of Saskatchewan	Helmle	Richard	Student	Biogeosciences
University of Saskatchewan	Karran	Daniel	Student	Hydrology
University of Saskatchewan	Leroux	Nicolas	Student	Hydrology
University of Toronto	Desloges	Joseph	Regular	Earth Surface Processes
University of Toronto	Mitchell	Carl	Regular	Biogeosciences
University of Toronto	Robinson	Alexis	Student	Hydrology
University of Toronto Mississauga	Brown	Laura	Regular	Hydrology
University of Toronto Mississauga	Munro	D. Scott	Regular	Hydrology
University of Toronto Mississauga	Dauginis	Alicia	Student	Earth Surface Processes
University of Toronto Mississauga	Mirza	Eisha	Student	Hydrology
University of Toronto Mississauga	Murfitt	Justin	Student	Hydrology
University of Victoria	Gibson	John	Regular	Hydrology
University of Victoria	Jerreat-Poole	Haven	Student	Hydrology
University of Victoria	Newton	Brandi	Student	Hydrology
University of Victoria	Taulu	Jasmine	Student	Hydrology
University of Washington Tacoma	Shugar	Daniel	Regular	Earth Surface Processes
University of Waterloo	Ameli	Ali A	Regular	Hydrology
University of Waterloo	Basu	Nandita	Regular	Hydrology
University of Waterloo	Burn	Donald	Regular	Hydrology
University of Waterloo	Craig	James	Regular	Hydrology
University of Waterloo	Davidson	Scott J.	Regular	Biogeosciences
University of Waterloo	Hardy	Mary Anne	Regular	Hydrology
University of Waterloo	Khomik	Myroslava	Regular	Biogeosciences
University of Waterloo	Kompanizare	Mazda	Regular	Hydrology
University of Waterloo	Lam	W. Vito	Regular	Biogeosciences
University of Waterloo	MacVicar	Bruce	Regular	Earth Surface Processes
University of Waterloo	Mai	Juliane	Regular	Hydrology
University of Waterloo	Petrone	Richard	Regular	Hydrology
University of Waterloo	Plach	Janina	Regular	Biogeosciences
University of Waterloo	Rezanezhad	Fereidoun	Regular	Biogeosciences
University of waterloo	Schiff	Sherry	Regular	Biogeosciences
University of Waterloo	Scott	Andrea	Regular	Hydrology
University of Waterloo	Soulis	Eric D.	Regular	Hydrology
University of Waterloo	Stone	Mike	Regular	Hydrology
University of Waterloo	Strack	Maria	Regular	Biogeosciences
University of Waterloo	Tolson	Bryan	Regular	Hydrology
University of Waterloo	Brown	Genevieve	Student	Hydrology
University of Waterloo	Byrnes	Danyka	Student	Biogeosciences
University of Waterloo	Carlow	Ryan	Student	Hydrology
University of Waterloo	Cheng	Frederick	Student	Hydrology
University of Waterloo	Coulas	Matthew	Student	Biogeosciences
University of Waterloo	De Haan	Kevin	Student	Hydrology
University of Waterloo	Devoie	Elise	Student	Hydrology
University of Waterloo	Elliott	James	Student	Hydrology

Affiliation	Last name	First name	Status	CGU Section
University of Waterloo	Gharedaghloo	Behrad	Student	Hydrology
University of Waterloo	Grant	Kirsten	Student	Hydrology
University of Waterloo	Grass	Sarah	Student	Hydrology
University of Waterloo	Han	Ming	Student	Hydrology
University of Waterloo	Higgins	Stephanie	Student	Biogeosciences
University of Waterloo	Kokulan	Vivekananthan	Student	Hydrology
University of Waterloo	Langs	Lindsey	Student	Hydrology
University of Waterloo	Lee	Konhee	Student	Hydrology
University of Waterloo	Liu	Hongli	Student	Hydrology
University of Waterloo	Marshall	Meredith	Student	Biogeosciences
University of Waterloo	Morison	Matt	Student	Hydrology
University of Waterloo	Neupane	Santosh	Student	Hydrology
University of Waterloo	Popovic	Natasa	Student	Hydrology
University of Waterloo	Prentice	Tyler	Student	Biogeosciences
University of Waterloo	Price	Dylan	Student	Biogeosciences
University of Waterloo	Ranjram	Mark	Student	Hydrology
University of Waterloo	Samson	Melani-Ivy	Student	Biogeosciences
University of Waterloo	Van Beest	Christine	Student	Biogeosciences
University of Waterloo	Van Huizen	Brandon	Student	Hydrology
University of Waterloo	Watt	Caitlin	Student	Hydrology
University of Western Ontario	Ashmore	Peter	Regular	Earth Surface Processes
University of Western Ontario	Peirce	Sarah	Regular	Earth Surface Processes
University of Western Ontario	Simonovic	Slobodan	Regular	Hydrology
University of Western Ontario	Goguen	Kayla	Student	Earth Surface Processes
University of Western Ontario	Mahmoudi	Mohammad	Student	Hydrology
University of Western Ontario	Sia	Maria Eloisa	Student	Biogeosciences
University of Western Ontario	Thayer	James	Student	Earth Surface Processes
University of Western Ontario	Tian	Jing	Student	Biogeosciences
University of Winnipeg	Ducharme	Adrienne	Student	Biogeosciences
Water's Edge	Gazendam	Ed	Regular	Earth Surface Processes
Wilfrid Laurier University	Carpino	Olivia	Regular	Hydrology
Wilfrid Laurier University	Haynes	Kristine	Regular	Biogeosciences
Wilfrid Laurier University	Rudy	Ashley	Regular	Earth Surface Processes
Wilfrid Laurier University	Young	Gordon	Regular	Hydrology
Wilfrid Laurier University	Ackley	Caren	Student	Hydrology
Wilfrid Laurier University	Walker	Branden	Student	Hydrology
York University	Young	Kathy	Regular	Hydrology
York University	Scheffel	Harold-Alexis	Student	Hydrology
Yukon Department of Environment	Janowicz	Richard	Regular	Hydrology
No affiliation	Champion	Emily	Student	Hydrology

Section 4 International Association of Meteorology and Atmospheric Sciences (IAMAS)

1. IAMAS-related research in Canada

Canada has a long history of carrying out research on topics associated with IAMAS. This report covers the research conducted across Canada over the four-year period from 2015-2019.

2. Research Institutes and Personnel

Research in Canada is concentrated in government, primarily within Environment and Climate Change Canada (ECCC), and in the university community.

There are several ECCC research centres in Canada. These include Recherche en Prévision Numérique (Numerical Weather Prediction Branch) in Dorval, Québec, the Canadian Centre for Climate Modelling and Analysis in Victoria, British Columbia, and the Climate Research Division in Downsview, Ontraio.

The university community includes many universities throughout the country. Several universities have a multiple faculty pursuing IAMAS research, such as Dalhousie, McGill, University of Alberta, University of British Columbia, University of Toronto, University Québec à Montréal, York University, and University of Waterloo, with many others that have some IAMAS research presence. This diffusion of IAMAS research across the academic sector has become a defining feature of IAMAS type research in Canada. For example, the White Paper on Atmosphere-Related Research in Canadian Universities (ARRCU) had 74 faculty signatories from more than 12 universities (ref. 1).

There is a large group of graduate students pursuing advanced degrees (M.Sc. and Ph.D.) in Canada. Among the largest programs, Dalhousie University has 13 graduate students, McGill University has 36, University Québec à Montréal has 26, and University of Toronto has 27. All graduate student numbers are from 2019.

3. Research Activities

Over the last four years, a substantial amount of research covering a range of weather, climate, and air quality topics has been performed.

3.1 Research Areas

Canadian research in meteorology and atmospheric sciences includes weather forecasting, air quality assessments and forecasts, seasonal climate prediction, historical and current climate change, and future climate change projections. The Canadian Meteorological and Oceanographic Society (CMOS) Annual Congress is a meeting that spans the breadth of research areas in Canada (https://www.cmos.ca/site/congress_past). From 2015-2018, the themes of this meeting have been "Tropics to Poles: Advancing Science in High Latitudes", "Monitoring and Adapting to Extreme Events", and "Future Earth: Weather, Oceans, Climate", and "Marine and Environmental Risks and Impacts".

3.2 Collaborative and Large Efforts

The last four years included part of the 5-year Climate Change and Atmospheric Research (CCAR, 2013-2017) that funded seven large research networks. These addressed atmospheric aerosols and clouds, the biogeochemistry of the Arctic ocean, atmosphere of the high Arctic, seasonal snow cover and sea ice prediction, regional-scale weather and climate processes and prediction, cold region hydrology, and coupling between the ocean and atmosphere.

Networks of Centres of Exccellence of Canada (NCEs) are designed to address major social, economic or health issues that require a collaborative approach and a wide range of expertise. There are two NCEs that have a substantial amount of activity in atmospheric sciences and meteorology. ArcticNet (2003-2019, http://www.arcticnet.ulaval.ca/) is focused on the impacts of climate change and modernizeation in the coastal Canadian Arctic. Marine Environmental, Observation, Prediction and Response Network (MEOPAR, 2012-2022, meopar.ca) is focused on better understanding and prediction of the impact of marine hazards on human activities and ecosystems.

4. Research Budgets

The research budgets over the period from 2015-2019 have seen changes in both directions. Individual university researchers in Canada are eligible for individual research program grants through NSERC's Discovery grants program. This program has had a 12% increase over period of 2014-2019 (Ref 3.).

The funding for large research networks funded by CCAR, $7 million per year in total, lapsed in 2017 without a replacement program (Ref. 2, 4). The Polar Environment Atmospheric Research Laboratory (PEARL) in Eureka, Nunvut was supported by CCAR and received an additional $1.6 million of federal funding to continue operation through Fall 2019 (Ref 5.)

5. Outlook

There is a substantial amount of international-level scientific activity by Canadian researchers in IAMAS subdisciplines. There have been unique contributions over the last four years (e.g., CCAR highlights, ref 2.) and there are challenges to future progress, particularly surrounding research funding. The community of universities researchers have made efforts to unify under ARRCU (ref. 1). ARRCU is presently a Special Interest Group of the Canadian Meteorological and Oceanographic Society. Beyond the funding challenge presented by the lapse of the CCAR program, this program was an important avenue for government and university scientists to collaborate. An issue of ongoing concern, then, is the capacity of this community to organize itself in order to engage in national-scale strategic research with an international profile. Thus there is a strong need for these legacy programs to make important links for Canadian contributions to meteorology and atmospheric sciences.

6. Canadian IAMAS Actions

While it is difficult to fully enumerate the totality of Canadian IAMAS actions, there are two international contributions that we highlight here. First, there is extensive participation (e.g. lead authorship and report review functions) in international Assessment reports, including the IPCC Special Report Global Warming of 1.5° C (https://www.ipcc.ch/sr15/) and the forthcoming IPCC Sixth Assessment Report (https://www.ipcc.ch/assessment-report/ar6/). Second, CMOS is co-convening, along with the Canadian Geophysical Union (CGU), the 27th General Assembly of the International Union of Geodesy and Geophysics in Montreal, Canada in July 2019.

7. Contributors to this Report

Timothy Merlis (McGill University), Paul Kushner (University of Toronto), Ian Folkins (Dalhousie University), Pierre Gauthier (UQAM), and Kaley Walker (University of Toronto)

8. References

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2. Evaluation of the Climate Change and Atmospheric Research (CCAR) Initiative, http://www.nserc-crsng.gc.ca/_doc/CCAREvaluation_e.pdf

3. NSERC 2018 Competition Statistics Discovery Grants, Research Tools and Instruments and Subatomic Physics Programs, http://www.nserc-crsng.gc.ca/NSERC-CRSNG/FundingDecisions-DecisionsFinancement/2019/2018DG-RTI-SP_e.pdf

4. Scientists brace for climate-fund cutoff, Ivan Semeniuk, The Globe and Mail, June 27. 2017 https://www.theglobeandmail.com/news/national/scientists-brace-for-cuts-as-federal-climate-funding-expires/article35484709/

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Section 5 International Association of Physical Sciences of the Ocean (IAPSO)

Activities in Canada 2015-2018

Jody M. Klymak & Peter Galbraith

IAPSO-Related Research in Canada

Canada has a large physical oceanography community. A minimal set was identified here of 72 scientists who were asked for input into this document. This included academic scientists and government lab scientists. This number probably under-estimates the IAPSO-related scientists in Canada; for instance a comprehensive list of people working on climate change was not included, despite many of them working a lot on ocean physics. Similarly the chemical oceanography community was not included in the list. These omissions were for brevity to have a more compact report, but it is probably desirable for future reports to be more broad-minded.

Of the 72 scientists who were asked, 35 filled out a questionaire, the results of which are summarized (and somewhat editorialized) below. This was a great response rate for an activity that required a finite amount of effort, and the community's input was very much appreciated.

As is clear below, there is a very healthy and large group of physical oceanographers in Canada; perhaps larger than the authors anticipated. Their work is summarized in the next section, but it worth noting the scope and breadth of the national efforts.

Research Areas and Selected Publications

Below we outline the state of physical oceanographic research in Canada with a bibliography that has been very roughly grouped by the type of often overlapping problems being approached. Respondents were asked to provide *five* representative publications for the years 2015–2018, so this is not an exhaustive list, of Canadian efforts, but rather what the researchers felt best represented their work.

State of the Ocean

A major activity undertaken in Canada is better quantification of the state of the ocean, across a broad range of scales and parameters. Measuring the state of the ocean is difficult given the large scales at play and the necessity of expensive and laborious *in-situ* observations. Included here are Government reports published annually by the scientists of the Atlantic Zone Monitoring Program. Also, of particular interest are better understanding the Arctic, the role of unexpected marine heat waves, and the interplay of ocean physics and ocean biological productivity.

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Bris, A. L., J. Fisher, H. Murphy, P. Galbraith, M. Castonguay, T. Loher, and D. Robert (2018). “Migration patterns and putative spawning habitats of Atlantic halibut (Hippoglossus hippoglossus) in the Gulf of St. Lawrence revealed by geolocation of pop-up satellite archival tags”. In: ICES Journal of Marine Science 75.1, pp. 135–147.

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State of the Ocean reports

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Ocean State Prediction

There is a large effort to better understand and be able to predict the state of the ocean, again spanning spatial scales from inland seas to the open ocean, and temporal scales from seasonal to climate time scales. A major theme is ocean state prediction under various climate change scenarios, predicting climate change in the Arctic, and better predicting ocean productivity.

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Modelling and laboratory processes studies

Canada has a healthy community of scientists working on idealized laboratory and numerical studies aimed at better understanding relevant and interesting ocean process. There is substantial work to isolate processes such as internal waves and eddies and better understand their dynamics. There are also a number of sensitivity studies that look at how more full-physics models respond to idealized forcing.

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Observational Process Studies

There is also a reasonable sized community directly observing ocean processes, despite the cost and effort involved in this style of work. The focus tends to be waves, either internal or surface, or lateral processes such as fronts and eddies.

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Technical Development

There are few Canadian groups involved in creating new technology, which is unfortunate given Canada’s historical leading role in this regard. (In fact one of the two citations below was actually carried out in France). Alex Hay’s group is the leading exception in academia, and some platform development is still carried out at the Bedford Institute of Oceanography. DFO’s Maurice-Lamontagne Institute has also played a large part in the development of a new automatic oceanography buoy equipped with profiling temperature-salinity, with MTE Inc, a private company based in Rimouski (QC). Ten of these buoys are deployed by DFO from the Pacific to the Atlantic.

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Graduate and post-Graduate Supervision

Physical oceanographers in Canada educate a good number of graduate students, despite the fact that a lot of activity is in government labs, and those labs do not have a direct educational mandate. The 35 respondents report 80 HQP who graduated or finished their postdocs during the reporting period. Of these, 41 were masters students, 35 doctorates, and 4 post-doctoral scholars.

Respondents to the survey were asked to provide present employment of graduated students. Many of these scholars were continuing in their studies, either as students or postdocs. Others found work directly in their field, or closely related ones. A few were reported to be employed in technical fields, but not oceanography related. Very few were reported to not have found work, or to be working in fields that did not use their degrees; of the 80, only 5 were reported as not necessarily using their degrees, and 12 were not reported. These are obviously optimistic statistics pointing towards demand for the quality and type of training students are receiving in physical oceanography in Canada.

Major Awards and Honors

Physical oceanographers in Canada are heavy participants in the Canadian Meteorological and Oceanographic Society and received a number of awards the last few years: Three physical oceanographers were awarded the President's prize, three the annual medal for applied oceanography. In addition, Ann Gargett, William Crawford, Keith Thompson, Michael Foreman, were each awarded the Tully medal for lifetime contributions to Canadian oceanography. One researcher received recognition in Norway with the Mohn Prize. An early career researcher was honoured with both the CNC-SCOR Early Career Ocean Scientist Award and an Alfred P. Sloan Research Fellowship. The community is very active in national and international conferences. One Canadian is an editor of the Journal of Physical Oceanography, one at Journal of Climate, and another an editor at Ocean Modelling; a number of members report receiving citations for excellence in refereeing from various international journals.

National and International Programs

There are a good number of Canadian Science programs that were vital to oceanographic research over the last five years. Canada's funding system has a base of funding available through "Discovery Grants", but these are often inadequate, particularly for sea-going research. One source of funds has been "Network Centres of Excellence", the main ones being ArticNet and MEOPAR (Marine Prediction). These support cores of scientists and also have open calls for research. The networks favour the inclusion of social research and the involvement of stakeholders in funded project.

The other large academic source of funds were a pair of Climate Change and Atmospheric Research programs. One of these was Arctic GEOTRACES, which had a small physical oceanography component to it, and VITALS, which looked at gas exchange in the Labrador Sea, and included more physics.

Recently there have been programs attached to institutes, in particular the Ocean Frontiers Institute at Dalhousie and Memorial that supports efforts in the Atlantic and Labrador Sea.

There is also a good number of government initiatives, some ongoing like the ocean monitoring programs (AZOMP, AZMP, Line P), and special projects like the Ocean Protection Plan. In fact the federal government has seen increased ocean funding in recent years, particularly related to establishing marine protected areas and better planning of responses to oil spills. Furthermore, there is a substantial effort to improve ocean forecasting underway (CONCEPTS) where nested regional NEMO models are being developed to provide operational ocean and ice forecasts.

Barriers to research

Barriers to research naturally focus around financial support, and more funding is always helpful. This is particularly important given the inherent expense of ocean research, but an expense that is justified by its inherent societal benefits. Increased support aside, there are a number of structural barriers identified by IAPSO scientists that might be addressed.

First, a number of respondents pointed out that the role of government labs in carrying out fundamental research, particularly on the observing side, has been substantially eroded over the last twenty years. There has been a major shift away from new instrument development and a struggle to keep seagoing gear in the water in the government labs as programs have shifted from long-scale curiousity driven research to short-term government-mandated programs, often narrowly focused on fisheries. This has been exacerbated by the fact that historically such work has also been supported by the US Office of Naval Research (US-ONR), a funding source that has all but dried up for Canadian labs. These changes threaten the long-term viability of Canadian oceanography, because without technical expertise and new innovations, Canadian research will atrophy. There were also a number of issues with travel and similar restrictions identified by government scientists as reducing their ability to have an international impact.

Unfortunately many of the issues raised on the government side are not being addressed on the academic side. There are no sustained programs available to keep technical staff developing and deploying instrumentation. Similarly dollars for shiptime have not increased for 20 years, and even if shiptime is available, there are few funding sources to pay for deployment on the ships. Hence most of the work cited above for ocean process studies is either funded by the Province of Quebec (where there are programs for medium scale projects) or via foreign funding sources like US-ONR. Relatedly, there is a general dearth of shiptime nationally, affecting all research areas. The existing fleet is very old, and in most cases past their operational life, and replacement vessels have been slow if they are forthcoming at all.

There have been laudable relatively large special programs like the CCAR programs (VITALs and GEOTRACES) that involved some physical oceanography. But these programs have not been renewed, and unsteady spurts of money are not a viable way to maintain research capacity. Similarly, special programs, networks, and chairs have seen large concentrations of money, but the scientific output of these efforts would charitably be described as "mixed". Part of the problem are the administrative overheads associated with these programs and multi-disciplinarity requirements that seek to tie social science and natural science together. Of course some oceanography can and should inform social sciences, and have societal applications, but basic curiousity-driven research is what ultimately leads to new understanding.

Respondents also identified a lack of organization amongst physical oceanographers and the oceanographic community as a whole. Many of us fall under the Canadian Meteorological and Oceanographic Society's umbrella, but while that organization covers a broad range of scientists, it does not attract membership from non-physical oceanographers who many of us consider our closest colleagues. There is an opportunity for a better way to organize oceanography in Canada, with physical oceanography within it.

Outlook and future themes

The community sees physical oceanography as crucial to better predictions of climate change. As discussed above, this will require better observations and better simulations. Fortunately, the community is at the point where capacity has increased for both activities, with more autonomous instrumentation on the observational side, and more simulation power on the prediction side. Continuing to push for resources for both these activities is seen as key.

A key part of better predictions is better parameterization of ocean mixing processes, particularly as ocean models achieve finer and finer resolution. There is a strong core of researchers across the country working on various aspects of ocean mixing, and key experiments can/should be agitated for to contribute to the global effort, particularly given Canada's wealth of "natural laboratories" in the fjords that incise much of our coast.

Not surprisingly, given the mandate of the Department of Fisheries and Oceans, there is strong support for better understanding the impact of ocean physics on ocean biology and chemistry. Many of the "missing terms" in bio/chemical models involve lateral advection and vertical mixing, and physical oceanographers can play a key role in helping constrain and parameterize these terms.

Finally, there is a strong recognition that understanding the physics of the ocean and the richness of the phenomenology there is as interesting a realm for curiousity-driven research as any other field. Often the practical parameterizations of tomorrow are due to discoveries that were driven purely by a curiousity about how the ocean works, and that curiousity should be supported even if a direct application with an identified societal stakeholder is not readily identifiable. Canada spends a lot of money on science that has no discernible societal benefit beyond technological spinoffs, simply because the fields are prestigious and of fascination to the public. The ocean is similarly fascinating, and has prestige in other countries, and Canadian scientists should promote the love of the sea and understanding beyond immediate societal payoff.

Section 6 International Association of Seismology and Physics of the Earth's Interior (IASPEI)

Major Areas of Research

Structural Seismology

The Canadian landmass preserves over 3 billion years of Earth's tectonic history, including the formation and evolution of cratonic lithosphere, the accretion of continental material via collisional tectonics and subduction processes, the development of rifted margins, and active tectonic processes. This broad range of tectonic processes also gives rise to a broad range of research under the general umbrella of structural seismology.

A number of researchers use controlled-source reflection/refraction seismology to image crustal structure ranging from the Archean to present. Notable areas of study include the rifted continental margins of eastern North America and their associated sedimentary basins, and the active subduction zone off the coasts of British Columbia and Alaska.

"Passive" or natural-source seismology is used extensively to investigate the structure and evolution of the crust, the upper mantle and the deep Earth, at spatial scales ranging from local (e.g. upper-crustal structure of basins and margins) to global. The wide variety of imaging techniques gives rise to a number of complementary seismic models of structure and anisotropy, and is used to probe fundamental questions in continental evolution. In eastern and central Canada, the main focus is the evolution of the Canadian Shield and its margins, whereas studies of the western regions provide new information on craton-Cordillera interaction and subduction-zone structure. A number of broadband seismic networks, both permanent and temporary, are in place across the country; these are used both for structural studies and seismic monitoring.

Research into seismic imaging techniques at different spatial scales and degrees of complexity is also active across Canada. Several researchers are investigating full-waveform inversion and seismic wavefields in complex media, with applications ranging from exploration-scale seismology to global seismic tomography.

Seismicity and Hazard Analysis

The Canadian National Seismograph Network (CNSN) forms the backbone for seismic monitoring in Canada and provides the bulk of data used for research related to Canadian seismicity. The CNSN is currently nearing completion of a major upgrade, which includes the replacement of single-component stations with three-component broadband instruments and a significant increase in the number of strong-motion instruments nationwide, most of which will be collocated with weak-motion instruments. Several regional networks, mostly operated by universities, and special deployments for specific research projects provide(d) additional coverage of earthquake activity in many regions of Canada.

In addition to routine monitoring of earthquake activity across Canada, the details of which are archived in a national database, there have been several focused seismicity studies on regions of interest. Many of these were undertaken to determine the background rates of natural seismicity in regions such as northeastern British Columbia, western Alberta and New Brunswick, which may be at risk of induced seismicity from current or future unconventional hydrocarbon extraction.

In-depth research related to seismicity can generally be categorized as either earthquake-specific or parameter-specific. Canadian seismologists made significant contributions to the understanding of the 2012 Haida Gwaii earthquake (M_W 7.8) sequence as can be seen by the many and varied papers of Canadian origin in the 2015 special issue of the *Bulletin of the Seismological Society of America* dedicated to that earthquake, as well as those published in other journals. Studies of small and moderate earthquakes have been numerous and tend to be focused on events that are considered somewhat unusual. Among these are the earthquake swarms in McAdam, New Brunswick and the Barrow Strait earthquake sequence in Canada's far north.

Significant progress has been made toward ensuring uniformity of magnitude attribution across Canada for use in hazard assessments. Successful research in this field includes the development of reliable conversion relations and an improved understanding of some issues related to them, such as the time dependence of some conversion relations. Magnitude research is ongoing with a particular emphasis on resolving inconsistencies or biases. Depths of earthquakes in Canada are often poorly resolved but there have been some successes in depth determinations for earthquakes, such as those occurring along the St. Lawrence Valley, through increased station density in some regions and the application of new methods in others.

The 5th Generation seismic hazard model for Canada was released and adopted for use in the 2015 National Building Code of Canada (NBCC). It is being adopted and applied to the provinces and territories. All supporting documentation has been published. Development of the 6th Generation seismic hazard map proposed for use in the 2020 NBCC is underway. New features of the 6th Generation model include the adoption of new ground motion relations, modification of some source zones, revisions to recurrence rates in the Cascadia subduction zone and the addition of fault sources in the southern Vancouver Island region. In the past, direct hazard calculations were performed for Site Class C only. The new version will allow for direct calculations for Site Classes A-E. The new hazard model will be developed using OpenQuake, a new open-source platform developed by the Global Earthquake Model Foundataion and a departure from the previous platform that had been in use in Canada for nearly three decades.

Induced Seismicity

Research on the topic of induced seismicity is thriving in Canada, with a particularly strong focus on understanding seismicity that is linked to oil and gas operations. Fruitful collaboration within seismology and related disciplines is occurring across a broad spectrum of organizations, including academic research groups across Canada, government agencies, regulatory bodies in several provinces and industry. Universities with academic groups (with leading faculty members) that are actively conducting research on induced seismicity include the University of Victoria (Honn Kao, Ed Nissen), the University of British Columbia (Amanda Bustin), the University of Calgary (David Eaton, Jan Dettmer, Joern Davidsen, Shawn Maxwell), the University of Alberta (Mirko van der Baan, Yu Jeffrey Gu), Western University (Robert Scherbakov, Gail Atkinson) and McGill University (Yajing Liu, James Kirkpatrick). Academic investigations benefit from collaboration with international groups as well as significant research within the Canadian seismology industry, including

Nanometrics (based in Ottawa) and Engineering Seismology Group (based in Kingston). At the federal level, Natural Resources Canada hosts a national program to investigate induced seismicity, and at the provincial level Geoscience BC and regulatory agencies in British Columbia and Alberta are at the forefront of basic and applied research. Organizations within the Canadian oil and gas industry, such as the Canadian Association of Petroleum Producers (CAPP) and the Canadian Society for Unconventional Resources (CSUR) are supporting applied research and workshops on induced seismicity. For example, CSUR collaborated with Western University and the University of Calgary (through the the Canadian Induced Seismicity Collaboration, www.inducedseismicity.ca) to host a major international workshop in Banff, Canada (October 24-27, 2018). New opportunities for collaborative international research are also emerging as part of the Canadian Cordillera Array (www.ccarray.org).

Fault-Zone Processes

A group of researchers has focused on earthquake source process studies o fboth natural/tectonic events and anthropogenically induced seismicity.

Station coverage in several active seismic zones in eastern Canada (western Québec, Charlevoix, Lower St-Lawrence) has been improved by temporary and permanent deployments, which leads to more complete seismicity catalogues and better constraints for source parameters. For example, inversions of earthquake focal mechanism solutions and stress drop estimates are now available for events as small as magnitude 2 in the Charlevoix area. High-precision seismicity relocation also provides clearer pictures of seismogenic structures that are broadly linked to regional geology.

In the western Canadian sedimentary basin (WCSB), fluid injection in the process of unconventional oil and gas exploration has been linked to the dramatic increase in seismicity in the past decade. In response, regional seismic station coverage in WCSB has gradually densified, supplemented by several local dense arrays in British Columbia and Alberta. Research has focused on 1) identifying the spatiotemporal correlation between seismicity and fluid injection history, 2) correlation with pre-existing geological structures, regional stress and deformation, 3) inversion of source parameters in order to discriminate natural versus induced events, 4) calibration of ground motion for development of earthquake hazard assessment models, and 5) numerical modeling to understand the physical mechanisms of earthquake triggering.

Several seismological and geodetic studies have focused on the Cascadia megathrust slip and subduction zone deformation. Episodic slow-slip events and non-volcanic tremors are continuously monitored in northern Cascadia. Three-dimensional subduction fault geometry, fluid pore pressure, and fault rheology variation is taken into consideration in earthquake cycle models, in order to understand the source mechanics of slow earthquakes and their potential interaction with megathrust rupture.

Geodynamic Modelling

The geological evolution of the Earth's surface is a direct result of the dynamical processes occurring in its interior. Mantle thermal convection is a primary process within terrestrial planets, but there are still fundamental questions about how the mantle circulation may drive plate tectonics. The tectonic plates represent the upper boundary layer of the mantle convection system, with plate motions giving rise in various ways to surface deformation (e.g., mountain building, earthquakes), volcanism, the formation and modification of continents and oceanic plates, and sedimentary basin formation. Geodynamics research in Canada involves scientists studying these geological/geophysical problems across a variety of spatio/temporal scales and using a range of approaches including analytical calculations, laboratory (physical) models, and numerical models. This geodynamic modelling is answering quantitatively how parameters control and processes drive the internal dynamics of the Earth and other planetary bodies.

Large-scale mantle convection models focus on the long-term thermomechanical evolution of the Earth's interior and the resulting surface plate motions. Recent studies demonstrate that variations in heat flow from the Earth's core and the presence of continental plates at the surface modulate the convective system, with implications for the mobility of tectonic plates and generation of mantle plumes. Other studies highlight the important roles of phase changes in the mid-mantle, iron-spin transition in the lower mantle, and compositional heterogeneities in the dynamics of the deep Earth. Convection models are also being applied to investigate the dynamics of the moon and other bodies, including super-Earths.

Regional-scale models address linkages between mantle dynamics and surface tectonics, with studies focussing on the dynamics of subduction and mountain-building at modern and ancient convergent margins (e.g., western North and South America, northern Canada, Europe, and New Zealand) and the effects of melt on shallow mantle dynamics (e.g., volcanism, the formation of melt bands at mid-ocean ridges). Key results are the recognition of vertical tectonics whereby gravitational removal of the mantle lithosphere induces observable deformation of the Earth's surface and the role of inherited lithospheric heterogeneities in controlling continental deformation. Other areas of study address the formation of continental cratons and their evolution over time, and important feedbacks between surface processes (e.g., erosion and sedimentation) and the Earth's interior.

Canadian researchers continue to develop new leading-edge modelling approaches, with current efforts focussing on full 3D codes and the inclusion of increasingly complex material properties. Researchers are also developing innovative techniques to characterize subsurface dynamics using machine-learning methods. Much of this numerical work utilizes resources from Compute Canada, a national consortium that provides infrastructure and services for large-scale advanced research computing.

Executive Summary information provided by F. Darbyshire, A. Bent and colleagues, D. Eaton, Y. Liu, C. Currie and R. Pysklywec.

IASPEI Institutions and Agencies

The following table shows the current list of IASPEI members, as well as their respective Institutions and primary research interests.

Institution	Professor	Research Interests
Carleton University	Dariush Motazedian	Earthquake Seismology
Columbia University	Mladen Nedimovic	Plate Tectonics
Geological Survey of Canada, Natural Resources Canada	Allison Bent	Earthquake Hazard Analysis
	John Adams	Earthquake Hazard Analysis
	Claire Perry	Earthquake Hazard Analysis
	John Cassidy	Earthquake Seismology
	Honn Kao	Earthquake Seismology
	Andrew Schaeffer	Earthquake Seismology
	Nathan Hayward	Earthquake Seismology
McGill University	Yajing Liu	Earthquake Seismology
Memorial University of Newfoundland		
	Jeremy Hall	Seismic Imaging
	Charles Hurich	Controlled Source Seismology
	Kim Welford	Controlled Source Seismology
Simon Fraser University	Andrew Calvert	Controlled Source Seismology
Université du Québec à Montréal	Fiona Darbyshire	Structure and Evolution of Continental Lithosphere
University of Alberta	Claire Currie	Geodynamics
	Yu Jeffrey Gu	Earthquake Seismology
	Mauricio Sacchi	Seismic Imaging and Inversion
	Mirko van der Baan	Seismic wave propagation
University of British Columbia	Michael Bostock	Structure and Seismicity of Subduction Zones
	Mark Jellinek	Plate Tectonics
University of Calgary	Dave Eaton	Microseismicity
	Hersh Gilbert	Plate Tectonics
	Jan Dettmer	Seismic Inversion
	Kristopher Innanen	Seismic Inversion
	Edward Krebes	Theoretical and Computational Seismology
	Rob Ferguson	Seismic Imaging
University of Manitoba	Andrew Frederiksen	Crustal Teleseismic Tomogrphy
University of Ottawa	Pascal Audet	Solid Earth Dynamics and Evolution
University of Saskatchewan	Igor Morozov	Structural Seismology
	Sam Butler	Exploration Geophysics

University of Toronto	Russell Pysklywec	Plate Tectonics
	Qinya Liu	Seismic Full Waveform Inversion
	Julian Lowman	Mantle and Core Heat Exchange
	Bernd Milkereit	
	Charly Bank	
University of Victoria	Stan Dosso	Geophysical inverse Theory
	Lucinda Leonard	Plate Tectonics
	Edward Nissen	Earthquake Seismolgy and Geodey and Tectonic Geomorphology
University of Western Ontario	Gerhard Pratt	Seismic Full Waveform Inversion
	Sheri Molnar	Earthquake Hazard Analysis
	Gail Atkinson	Engineering Seismology
	Robert Shcherbakov	Statistical And Numerical Modelling
	Kristy Tiampo[1]	*Inversion and Numerical Modelling*

1. *Note that Professor Kristy Tiampo left the University of Western Ontario in 2015 to take a faculty position at the University of Boulder, Colorado.*

Publications

The following is a compilation of publications by Canadian IASPEI members from 2014 to 2018.

M AbuAisha, D Eaton, J Priest, R Wong, B Loret, AH Kent. Fully coupled hydro–mechanical controls on non-diffusive seismicity triggering front driven by hydraulic fracturing. Journal of Seismology, 1-13 2018

M AbuAisha, DW Eaton, J Priest, R Wong. Hydro-mechanically coupled FDEM framework to investigate near–wellbore hydraulic fracturing in homogeneous and fractured rock formations. Journal of Petroleum Science and Engineering 154, 100-113, 2017

M AbuAisha, B Loret, DW Eaton. Enhanced geothermal systems (EGS): hydraulic fracturing in a thermo-poroelastic framework. Journal of Petroleum Science and Engineering 146, 1179-1191, 2016

Afanasiev, Michael V and Pratt, R Gerhard and Kamei, Rie and McDowell, Glenn. (2014). Waveform based simulated annealing of crosshole transmission data: A semi-global method for estimating seismic anisotropy. Geophysical Journal International. 199(3): 1586-1607.

Aghaei, O., Nedimovic, M. R., Marjanovic, M., Carbotte, S. M., Canales, J.P., Carton, H. and Nikic, N., 2017, Constraints on melt content of o-axis magma lenses at the East Pacic Rise from analysis of 3-D seismic amplitude variation with angle of incidence, J. Geophys. Res. Solid Earth, Vol. 122, No.6, doi:10.1002/2016JB013785, 4123-4142.

Aghaei, O., Nedimovic, M. R., Carton, H., Canales, J. P., Carbotte, S. M. and Mutter, J. C., 2014, Crustal thickness and Moho character of the fast-spreading East Pacic Rise from 9 degree 42'-57'N from poststack-migrated 3D MCS data, Geochem. Geophys. Geosyst., Vol. 15, doi:10.1002/2013GC005069, 634-657.

A.E.Aksu, J. Hall, T.J. Calon, P. Günes, M.C. Barnes and J.C. Cranshaw. 2018. Corrigendum to "Messinian evaporites across the Anaximander Mountains, Sırrı Erinç Plateaun and the Rhodes and Finike basins, eastern Mediterranean Sea" [Marine Geology, 395}, 48-64, Marine Geology, 401, 1.

A.E.Aksu, J. Hall, T.J. Calon, P. Günes, M.C. Barnes and J.C. Cranshaw. 2018. Messinian evaporites across the Anaximander Mountains, Sırrı Erinç Plateaun and the Rhodes and Finike basins, eastern Mediterranean Sea. Marine Geology, 395, 48-64.

A.E. Aksu, T. Calon, J.Hall, B. Kurtboğan, S. Gürçay and G. Çifçi. 2014. Complex interactions of fault fans developed in a strike-slip system: Kozan fault zone, eastern Mediterranean Sea. Marine Geology, 351, 91-107.

A.E. Aksu, S. Walsh-Kennedy, J. Hall, R.N. Hiscott, C. Yaltırak, S.D. Akhun, and G. Çifçi. 2014. The Pliocene-Quaternary evolution of the Cilicia and Adana basins, eastern Mediterranean: special reference to the development of the Kozan fault zone. Tectonophysics, 622, 22-43.

A.E. Aksu, J. Hall, C. Yaltırak, E. Çınar, M. Küçük and G. Çifçi. 2014. Late Miocene – Recent evolution of the Finike basin and its linkages with the Beydağlari complex and the Anaximander Mountains, eastern Mediterranean. Tectonophysics, 635, 59-79.

J Akram, DW Eaton. 1D layered velocity models and microseismic event locations: synthetic examples for a case with a single linear receiver array. Journal of Geophysics and Engineering 14 (5), 1215, 2017

J Akram, DW Eaton. Refinement of arrival-time picks using a cross-correlation based workflow. Journal of Applied Geophysics 135, 55-66, 2016

J Akram, DW Eaton. A review and appraisal of arrival-time picking methods for downhole microseismic data: Arrival-time picking methods. Geophysics 81 (2), KS71-KS91, 2016

Alinia, H.S., Tiampo, K.F., Samsonov, S.V. Simplified one-dimensional methodology to retrieve the seasonal amplitude of zenith tropospheric delay on GPS data, *Radio Science*, resubmitted October 2018.

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Alinia, H.S., Tiampo, K.F., James, T.S. GPS coordinate time series measurements in Ontario and Quebec, Canada, *Journal of Geodesy*, doi:10.1007/s00190-016-0987-5, 2017.

Ammirati, J.-B., A. Venerdini, J. M. Alcacer, P. Alvarado, S. Miranda, and H. Gilbert (2018), New insights on regional tectonics and basement composition beneath the eastern Sierras Pampeanas (Argentine back-arc region) from seismological and gravity data, Tectonophysics, 740, 42-52, doi:10.1016/j.tecto.2018.05.015.

Amos, C. B., Audet, P., Hammond, W. C., Bürgmann, R., Johansson, I., & Blewitt, G., 2014, Uplift and seismicity driven by groundwater depletion in central California, *Nature*, 509, 483-486.

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Current HQP

The following table displays the current Highly Qualified Personnel (HQP) for the academic year 2018 at each of the participating Institutions.

University	Total Professors	Total PhD Students	Total MSc Students	Total Postdoctoral Fellows/Ras
University of Western Ontario	5	14	11	6
University of Ottawa	1	5	7	2
University of Alberta	4	14	8	4
Université du Québec à Montréal	1	1	3	1
Memorial University of Newfoundland	4	7	11	3
University of Saskatchewan	2	5	3	1
Carleton University	1	1	1	1
University of Manitoba	1	-	4	-
Geological Survey of Canada, Natural Resources Canada	7	-	-	-
University of Toronto	5	10	10	7
University of Calgary	6	13	8	3
Simon Fraser University	1	2	2	
McGill University	1	3	6	4
University of Victoria	3	10	10	2
University of British Columbia	2	2	8	1
Columbia University	1	6	4	4

List of Conferences and Workshops Attended

The following table displays all major academic conferences and workshops (as well as the specific years attended) by IASPEI members from 2014 to 2018

Name of Conference/Workshop	Years Attended
AGCC	2018
AGU	2014, 2015, 2016, 2017, 2018
AOGS	2018
Arctic Technology Conference	2016
ASA	2017, 2018
Association for the Sciences of Limnology and Oceanography	2018
ASEG	2016
Atlantic Continental Margins Conference	2014, 2018
BC Geophysical Society Symposium	2018
BCGS	2018
Canadian Geotechnical Conference	2017, 2018
CGU	2014, 2015, 2016, 2017, 2018
China Geoscience Union	2014
CRHNet	2016, 2018
CTG	2018
CTW	2017
DEEP	2018
EAGE	2014, 2015, 2016, 2017, 2018
Earthscope National Meeting	2017
EGU	2014, 2015, 2016, 2017, 2018
EON-ROSE/CCarray workshops	2016, 2018
European Seismological Commission General Assembly	2018
GAC-MAC	2015, 2016
GEESD	2018
GeoConvention	2014, 2018
Geological Society of America Annual Meeting	2014, 2017
GeoPRISMS	2016
German Geophysical Society	2015
GSA	2014, 2015, 2016, 2017, 2018
IASPEI	2017
Inuvik Petroleum Show	2014
NAG	2018
NCEE	2014
NSF	2016, 2018
OBSIP Symposium	2015, 2017
Paleoseismology, Archaeoseismology and Active	2017

Tectonics	
PBD	2017
SEG	2014, 2015, 2016, 2017, 2020
SEISMIX	2016
Southern California Earthquake Center Annual Meeting	2014
Seismological Society of America Annual Meeting	2014, 2015, 2016, 2017, 2018
STATSEI	2015, 2017
TransAlta Meeting on Induced Seismicity	2014
UAC	2015
UNAVCO Science Workshop	2016, 2018
World Conference on Earthquake Engineering	2017
WHOI	2018
YGF	2016, 2017, 2018

Major Awards

Please find a list of major achievements and awards granted to IASPEI members from 2014 to 2018 below, sorted by academic year.

2014

Dr. Gail Atkinson was appointed as a Fellow of the Royal Society of Canada
Dr. Gail Atkinson was appointed as the Industrial Research Chair in Induced Seismicity Hazards for NSERC/Transalta/Nanometrics
Dr. Edward Krebes was awarded for 15 years of Dedicated Service from the Association of Professional Engineers and Geoscientists of Alberta
Dr. Lucinda Leonard was awarded the GSA Bulletin Exceptional Reviewer Recognition

2015

Dr. Pascal Audet was awarded the Personnalité de la semaine by Radio-Canada/Le Droit
Dr. Pascal Audet was awarded the Early Researcher Award by the Ministry of Research and Innovation Ontario
Dr. Pascal Audet was awarded the Sloan Research Fellowship in Physics by the Alfed P. Sloan Foundation
Dr. Jan Dettmer was appointed as a Fellow of the Acoustical Society of America from 2015 to 2018
Dr. Mauricio Sacchi was appointed Editor-In-Chief of Geophysics

2016

Dr. Pascal Audet was awarded the Excellence in Media Relations Award by the University of Ottawa in 2016
Dr. Pascal Audet was appointed the University Research Chair in Solid Earth Geophysics at University of Ottawa from 2016 to 2021
Dr. Gail Atkinson was awarded the J. Tuzo Wilson Award by the Canadian Geophysical Union
Dr. Gail Atkinson was awarded the Gzowki Medal for the best paper in Civil Engineering by the Canadian Society of Civil Engineering
Dr. Fiona Darbyshire was renewed as a Tier II Canada Research Chair in Geophysics
Dr. Gerhard Pratt was awarded the Virgil Kauffman Gold Medal by the Society of Exploration Geophysics
Dr. Robert Shcherbakov was awarded the American Geophysical Union 2016 Editor's Citation

2017

Dr. Pascal Audet was awarded the Young Researcher of the Year Award by the University of Ottawa

Dr. Jan Dettmer was awarded the A.B. Wood Medal by the Institute of Acoustics

Dr. Edward Nissen was awarded the Canada Foundation for Innovation John R. Evans Leaders Fund, the British Columbia Knowledge Development Fund, and the Canada Foundation for Innovation Innovation Fund
Dr. Edward Nissen was appointed as a Canada Research Chair (Tier 2) in Geophysics
Dr Hersh Gilbert was awarded the JGR Editor's Highlight
Dr. Yajing Liu was awarded the Young Scientist Award by the Canadian Geophysics Union

2018

Dr. Pascal Audet was awarded the Young Scientist Award by the Canadian Geophysical Union

Dr. Pascal Audet was a Member of the College of New Scholars, Artists and Scientists for the Royal Society of Canada

Dr Hersh Gilbert was awarded the GSA Outstanding Publication
Dr. Jeremy Hall was awarded the Professional Geoscientists Award by Geoscientists Canada
The 2018 CSEG Symposium was held in honor of Dr. Mauricio Sacchi

Comments on Research Budgets

The following table displays all sources of academic funding received by IASPEI members from 2014 to 2018

Funding Source
National Earthquake Hazards Reduction Program (USGS)
Bruce Borehole Seismic Monitoring Project
Canada First Research Excellence Fund (CFREF)
Canadian Foundation of Innovation (CFI)
Consortium for Research in Elastic Wave Exploration Seismology
Dept. of Defence
Discovery Geophysics International
Emergency Management British Columbia (EMBC)
Funding from Participating Universities
Geological Survey of Canada (GSC) / Natural Resources Canada (NRCAN)
Geoscience BC
Institute for Catastrophic Loss Reduction (ICLR)
Ministry of Research and Innovation Ontario
Ministry Transportation of Ontario (MTO)
Natural Sciences and Engineering Research Council of Canada (NSERC)
National Science Foundation (NSF)
Office of Naval Research
Orthogonal Geophysics Inc
Pawsey Supercomputing Centre
SNC-Lavalin
Southern Ontario Seismographic Network (SOSN- OPGN). 2015
Strategic Environmental Research and Development Program (SERDP)
The City of Calgary
TransAlta/Nanometrics
Orthogonal Geophysics Inc
Pawsey Supercomputing Centre
SNC-Lavalin
Southern Ontario Seismographic Network (SOSN- OPGN). 2015
Strategic Environmental Research and Development Program (SERDP)
The City of Calgary
TransAlta/Nanometrics

Summary of Achievements

IASPEI activities during 2014-2018 in Canada continued to be healthy and strong. A total of 27 awards were received and 224 HQP were trained by our 45 active research (professor) members. Each individual researcher maintains an independent research program; funding was obtained from 24 distinct agencies or partners.

Large-scale multi-year funding in Canadian seismology research has been directed towards induced seismicity, seismic hazard mapping, … Natural Resources Canada employs ~15 seismologists that locate and catalogue earthquake events in Canada, perform seismic research, with a few personnel focused on updating the national seismic hazard model and map in a 5-year interval tied to the National Building Code cycle. In 2016, many active seismology researchers in Canada came together to discuss a future long-vision study seismic study of our country with focus on passive-source and earthquake seismology. Past success included LITHOPROBE, a multi-decade multi-million dollar effort to image the Canadian crust from coast to coast, using active-source and earthquake seismology. Researchers wrote and presented white papers at three workshops held across the country in 2016-2017. An NSERC CREATE application was submitted for the proposed "Canadian Cordillera Array" pilot project by Dr. David Eaton with co-investigators and collaborators. We hope that this project will pave the way for a long-term goal of multi-disciplinary study across Canada through the "EON-ROSE" Earth Observing Network initiative in the future.

As data treatment, analysis and modelling techniques become increasingly sophisticated, and use increasingly large data sets, access to high-performance computing is highly important to IASPEI activities. The Compute Canada consortium has proved invaluable for facilitating such access, and we hope that this initiative is able to continue in the long term.

Section 7 International Association of Vulcanology and Chemistry of the Earth's Interior (IAVCEI)

Activities in Canada: 2014-2018

Compiled by Glyn Williams-Jones, Department of Earth Sciences, Simon Fraser University and Nathalie Vigouroux-Caillibot, Department of Earth and Environmental Sciences, Douglas College

1. IAVCEI-Related Research in Canada

The primary challenge facing IAVCEI members in Canada is the still very limited public awareness of the presence of significant and geologically young volcanic systems. This is compounded by a prolonged period of insufficient funding for fundamental and applied science in Canada; the funding situation is worse for researchers in the smaller institutions. As such, IAVCEI researchers have had to deal with only marginal funding and the associated difficulty of recruiting and supporting talented graduate students and PDFs.

In spite of this, Canadian-lead research in volcanology and igneous petrology is ongoing and nation wide. The research is broad and inherently multidisciplinary with a focus on both national and international volcanic/magmatic systems. Approaches run the spectrum from theoretical research into the physical processes driving volcanism to experimental (analogue and numerical) geophysical and geochemical studies informed by detailed mapping and monitoring of ancient and modern magmatic systems. Given Canada's strength in the resource sector, many researchers' work also naturally overlaps with fundamental and applied research in the mineral and energy sector.

1.1. Research areas & Selected publications (Canadian researchers in bold)

1.1.1. Physical volcanology

Research focussing on physical volcanology processes is alive and well and centred around a handful of Canadian volcanologists, mainly in university research labs. These include (but are not limited to) John Stix at McGill University, whose team has continued their research into caldera collapse mechanisms and structures. Harold Gibson and his students at Laurentian University have pursued research into ancient komatiite volcanics from northern Canada. Kelly Russell from the University of British Columbia and his students and colleagues have pursued their pioneering work on the glacio-volcanic deposits from western and northwestern Canada. Ongoing work by Glyn Williams-Jones from Simon Fraser University and his students and colleagues is looking into eruption dynamics of a recent basaltic cinder cone eruption in western-central British Columbia. Pierre Simon Ross from the Institut National de Research Scientifique in Quebec City and his students continue their work on maar-diatreme volcanoes. Canadian volcanologists have also focussed their research attention on young/active volcanoes worldwide including ongoing projects in Hawaii by Brian Cousens and his students and collaborators.

- Bélanger, C. and **Ross, P.S.**, 2018. Origin of nonbedded pyroclastic rocks in the Cathedral Cliff diatreme, Navajo volcanic field, New Mexico. *Bulletin of Volcanology*, *80*(7), p.61.
- **Canil, D.**, Mihalynuk, M. and Lacourse, T., 2018. Discovery of modern (post-1850 CE) lavas in south-central British Columbia, Canada: Origin from coal fires or intraplate volcanism? *Lithos*, *296*, pp.471-481.
- **DeWolfe, Y.M.** and Pittman, N., 2018. Subaqueous strombolian eruptions, and eruption-fed pyroclastic deposits in a Paleoproterozoic rifted-arc: Hidden formation, Flin Flon, Canada. *Precambrian Research*, *316*, pp.48-65.
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- Seropian, G. and **Stix, J.**, 2018. Monitoring and forecasting fault development at actively forming calderas: An experimental study. *Geology*, *46*(1), pp.23-26.
- **Stix, J.**, J.M. de Moor, J. Rüdiger, A. Alan, E. Corrales, F. D'Arcy, J.A. Diaz, and M. Liotta, 2018. Using drones and miniaturized instrumentation to study degassing at Turrialba and Masaya volcanoes, Central America. *Journal of Geophysical Research*, 123, pp. 6501-6520.
- Wilson, A.M. and **Russell, J.K.**, 2018. Quaternary glaciovolcanism in the Canadian Cascade volcanic arc—Paleoenvironmental implications. *GSA Special Paper,* 538
- **Higgins, M.D.**, Hankard, F., Ganerød, M. and Van der Voo, R., 2017. The vesicular Sainte-Sophie dykes: a chemically distinct, near-surface facies of the Grenville Dyke Swarm? *Canadian Journal of Earth Sciences*, *55*(3), pp.241-251.
- **Ross, P.S.**, Núñez, G.C. and Hayman, P., 2017. Felsic maar-diatreme volcanoes: a review. *Bulletin of Volcanology*, *79*(2), p.20.
- Coumans, J.P. and **Stix, J.**, 2016. Caldera collapse at near-ridge seamounts: an experimental investigation. *Bulletin of Volcanology*, *78*(10), p.70.
- Kennedy, B., **Stix, J.**, Hon, K., Deering, C. and Gelman, S., 2016. Magma storage, differentiation, and interaction at Lake City caldera, Colorado, USA. *Bulletin*, *128*(5-6), pp.764-776.
- Nikitczuk, M.P., **Schmidt, M.E.** and Flemming, R.L., 2016. Candidate microbial ichnofossils in continental basaltic tuffs of central Oregon, USA: Expanding the record of endolithic microborings. *Bulletin*, *128*(7-8), pp.1270-1285.
- **Cousens, B.L.** and Clague, D.A., 2015. Shield to rejuvenated stage volcanism on Kauai and Niihau, Hawaiian Islands. *Journal of Petrology*, *56*(8), pp.1547-1584.
- Richan, L., **Gibson, H.L.**, Houlé, M.G. and Lesher, C.M., 2015. Mode of emplacement of Archean komatiitic tuffs and flows in the Selkirk Bay area, Melville Peninsula, Nunavut, Canada. *Precambrian Research*, *263*, pp.174-196.
- Delpit, S., **Ross, P.S.** and Hearn, B.C., 2014. Deep-bedded ultramafic diatremes in the Missouri River Breaks volcanic field, Montana, USA: 1 km of syn-eruptive subsidence. *Bulletin of Volcanology*, *76*(7), p.832.
- **Russell, J.K.**, Edwards, B.R., Porritt, L. and Ryane, C., 2014. Tuyas: a descriptive genetic classification. *Quaternary Science Reviews*, *87*, pp.70-81.

1.1.2. Formation of magmatic systems

Understanding the formation and development of magmatic systems from a petrological, geochemical, and tectonic perspective has been the focus of much of the recent research in Canada, including, but not limited to, continued work by Michael Higgins from the University du Québec à Chicoutimi and his collaborators on the magmatic processes provided by growing crystals. Derek Thorkelson and his students at Simon Fraser University pursued research into magmatic-tectonic links. Ian Coulson (University of Regina) and his students and colleagues have been active using isotope geochemistry to study the nature of the mantle source of Mesozoic mafic dikes in China. Dominique Weis from the University of British Columbia and her students and colleagues have been working on deciphering the mantle sources beneath both Hawaii and the Cascades/Garibaldi volcanic belts using geochemistry. Laurence Coogan (University of Victoria) and his students and colleagues have continued their work on MORB petrology and geochemistry. Mariek Schmidt and her group (Brock University) are actively applying their understanding of magmatic systems to new data from the Martian surface.

- Flaherty, T., Druitt, T.H., Tuffen, H., **Higgins, M.D.,** Costa, F., Cadoux, A., 2018. Multiple timescale constraints for high-flux magma chamber assembly prior to the Late Bronze Age eruption of Santorini (Greece). *Contributions to Mineralogy and Petrology*, *173*(9), p.75.
- Liu, S., Feng, C., Santosh, M., Feng, G., **Coulson, I.M.,** Xu, M., Guo, Z., Guo, X., Peng, H. and Feng, Q., 2018. Integrated elemental and Sr-Nd-Pb-Hf isotopic studies of Mesozoic mafic dykes from the eastern North China Craton: implications for the dramatic transformation of lithospheric mantle. *Journal of Geodynamics*, *114*, pp.19-40.
- Sarjoughian, F., **Lentz, D.**, Kananian, A., Ao, S. and Xiao, W., 2018. Geochemical and isotopic constraints on the role of juvenile crust and magma mixing in the UDMA magmatism, Iran: evidence from mafic microgranular enclaves and cogenetic granitoids in the Zafarghand igneous complex. *International Journal of Earth Sciences*, *107*(3), pp.1127-1151.
- Verbaas, J., **Thorkelson, D.J.**, Milidragovic, D., Crowley, J.L., Foster, D., Gibson, H.D. and Marshall, D.D., 2018. Rifting of western Laurentia at 1.38 Ga: The Hart River sills of Yukon, Canada. *Lithos*, *316*, pp.243-260.
- Bray, B., **Stix, J.** and **Cousens, B.**, 2017. Mafic replenishment of multiple felsic reservoirs at the Mono domes and Mono Lake islands, California. *Bulletin of Volcanology*, *79*(7), p.54.
- **Canil, D.** and Fellows, S.A., 2017. Sulphide–sulphate stability and melting in subducted sediment and its role in arc mantle redox and chalcophile cycling in space and time. *Earth and Planetary Science Letters*, *470*, pp.73-86.
- **Cousens, B., Weis, D.**, Constantin, M. and Scott, S., 2017. Radiogenic isotopes in enriched mid-ocean ridge basalts from Explorer Ridge, northeast Pacific Ocean. *Geochimica et Cosmochimica Acta*, *213*, pp.63-90.
- Eyuboglu, Y., Dudas, F.O., **Thorkelson, D.**, Zhu, D.C., Liu, Z., Chatterjee, N., Yi, K. and Santosh, M., 2017. Eocene granitoids of northern Turkey: Polybaric magmatism in an evolving arc–slab window system. *Gondwana Research*, *50*, pp.311-345.

- Harrison, L.N., **Weis, D.** and Garcia, M.O., 2017. The link between Hawaiian mantle plume composition, magmatic flux, and deep mantle geodynamics. *Earth and Planetary Science Letters*, *463*, pp.298-309.
- Mullen, E.K., **Weis, D.**, Marsh, N.B. and Martindale, M., 2017. Primitive arc magma diversity: new geochemical insights in the Cascade Arc. *Chemical Geology*, *448*, pp.43-70.
- **Coogan, L.A.** and Dosso, S.E., 2016. Quantifying Parental MORB Trace Element Compositions from the Eruptive Products of Realistic Magma Chambers: Parental EPR MORB are Depleted. *Journal of Petrology*, *57*(11-12), pp.2105-2126.
- Faak, K., **Coogan, L.A.** and Chakraborty, S., 2015. Near conductive cooling rates in the upper-plutonic section of crust formed at the East Pacific Rise. *Earth and Planetary Science Letters*, *423*, pp.36-47.
- Garcia, M.O., **Weis, D.**, Jicha, B.R., Ito, G. and Hanano, D., 2016. Petrology and geochronology of lavas from Ka ʻula Volcano: Implications for rejuvenated volcanism of the Hawaiian mantle plume. *Geochimica et Cosmochimica Acta*, *185*, pp.278-301.
- Qi, Y., Hu, R., Liu, S., **Coulson, I.M.**, Qi, H., Tian, J. and Zhu, J., 2016. Petrogenesis and geodynamic setting of Early Cretaceous mafic–ultramafic intrusions, South China: A case study from the Gan–Hang tectonic belt. *Lithos*, *258*, pp.149-162.
- **Schmidt, M.E.**, Schrader, C.M., Crumpler, L.S., Rowe, M.C., Wolff, J.A. and Boroughs, S.P., 2016. Megacrystic pyroxene basalts sample deep crustal gabbroic cumulates beneath the Mount Taylor volcanic field, New Mexico. *Journal of Volcanology and Geothermal Research*, *316*, pp.1-11.
- **Thorkelson, D.J.** and Laughton, J.R., 2016. Paleoproterozoic closure of an Australia–Laurentia seaway revealed by megaclasts of an obducted volcanic arc in Yukon, Canada. *Gondwana Research*, *33*, pp.115-133.
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- **Schmidt, M.E.**, Campbell, J.L., Gellert, R., Perrett, G.M., Treiman, A.H., Blaney, D.L., Olilla, A., Calef, F.J., Edgar, L., Elliott, B.E. and Grotzinger, J., 2014. Geochemical diversity in first

rocks examined by the Curiosity Rover in Gale Crater: Evidence for and significance of an alkali and volatile-rich igneous source. *Journal of Geophysical Research: Planets*, *119*(1), pp.64-81.

1.1.3. Geophysical imaging of active volcano-magmatic systems

Canadian-led research into the geophysical imaging of active magmatic systems has naturally focused on more active systems outside of Canada, especially the USA and Latin America, including ongoing research into the mechanisms of magma storage, eruption and passive degassing at volcanoes in Nicaragua by Glyn Williams-Jones and his students and colleagues. This same group have also been active imaging magmatic systems in the Andes and New Zealand. Martyn Unsworth of the University of Alberta has also been focusing on the volcanoes of the high Andes to image the magmatic plumbing system of these large systems. Sergey Samsonov with NRCAN in Ottawa and his colleagues have been very active using InSAR to model the geometry and deformation of magmatic plumbing systems.

- Cordell, D., **Unsworth, M.J.** and Díaz, D., 2018. Imaging the Laguna del Maule Volcanic Field, central Chile using magnetotellurics: Evidence for crustal melt regions laterally-offset from surface vents and lava flows. *Earth and Planetary Science Letters*, *488*, pp.168-180.
- Delgado, F., Pritchard, M., **Samsonov, S.** and Córdova, L., 2018. Renewed post-eruptive uplift following the 2011-2012 rhyolitic eruption of Cordón Caulle (Southern Andes, Chile): evidence for transient episodes of magma reservoir recharge during 2012-2018. *Journal of Geophysical Research: Solid Earth*.
- Lundgren, P., Nikkhoo, M., **Samsonov, S.V.**, Milillo, P., Gil-Cruz, F. and Lazo, J., 2017. Source model for the Copahue volcano magma plumbing system constrained by InSAR surface deformation observations. *Journal of Geophysical Research: Solid Earth*, *122*(7), pp.5729-5747.
- Miller, C.A., **Williams-Jones, G.**, Fournier, D. and **Witter, J.**, 2017. 3D gravity inversion and thermodynamic modelling reveal properties of shallow silicic magma reservoir beneath Laguna del Maule, Chile. *Earth and Planetary Science Letters*, *459*, pp.14-27.
- Reyes-Wagner, V., Díaz, D., Cordell, D. and **Unsworth, M.**, 2017. Regional electrical structure of the Andean subduction zone in central Chile (35–36 S) using magnetotellurics. *Earth, Planets and Space*, *69*(1), p.142.
- **Samsonov, S.V.**, Feng, W., Peltier, A., Geirsson, H., d'Oreye, N. and Tiampo, K.F., 2017. Multidimensional Small Baseline Subset (MSBAS) for volcano monitoring in two dimensions: Opportunities and challenges. Case study Piton de la Fournaise volcano. *Journal of Volcanology and Geothermal Research*, *344*, pp.121-138.
- Comeau, M.J., **Unsworth, M.J.** and Cordell, D., 2016. New constraints on the magma distribution and composition beneath Volcán Uturuncu and the southern Bolivian Altiplano from magnetotelluric data. *Geosphere*, *12*(5), pp.1391-1421.
- MacQueen, P., Zurek, J. and **Williams-Jones, G.**, 2016. Connected magma plumbing system between Cerro Negro and El Hoyo Complex, Nicaragua revealed by gravity survey. *Journal of Volcanology and Geothermal Research*, *327*, pp.375-384.
- Miller, C.A. and **Williams-Jones, G.**, 2016. Internal structure and volcanic hazard potential of Mt Tongariro, New Zealand, from 3D gravity and magnetic models. *Journal of Volcanology and Geothermal Research*, *319*, pp.12-28.

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- Lundgren, P., **Samsonov, S.V.**, López Velez, C.M. and Ordoñez, M., 2015. Deep source model for Nevado del Ruiz Volcano, Colombia, constrained by interferometric synthetic aperture radar observations. *Geophysical Research Letters*, *42*(12), pp.4816-4823.
- Lundgren, P., Kiryukhin, A., Milillo, P. and **Samsonov, S.**, 2015. Dike model for the 2012–2013 Tolbachik eruption constrained by satellite radar interferometry observations. *Journal of Volcanology and Geothermal Research*, *307*, pp.79-88.
- Zurek, J., **Williams-Jones, G.**, Trusdell, F. and Martin, S., 2015. The origin of Mauna Loa's Nīnole Hills: Evidence of rift zone reorganization. *Geophysical Research Letters*, *42*(20), pp.8358-8366.
- Wannamaker, P.E., Evans, R.L., Bedrosian, P.A., **Unsworth, M.J.**, Maris, V. and McGary, R.S., 2014. Segmentation of plate coupling, fate of subduction fluids, and modes of arc magmatism in Cascadia, inferred from magnetotelluric resistivity. *Geochemistry, Geophysics, Geosystems*, *15*(11), pp.4230-4253.

1.1.4. Geochemical imaging of volcanic systems

Similarly, geochemical imaging of actively degassing volcanic systems has made important inroads in understanding volcanoes in Latin America and Southeast Asia. Canadian researchers have access to some state-of-the-art analytical facilities and work out of McGill (John Stix and Kim Berlo) and Simon Fraser University (Glyn Williams-Jones and Nathalie Vigouroux) on volcanoes in Indonesia and Central America has provided insight into the nature of persistently degassing volcanoes.

- Zurek, J., Moune, S., **Williams-Jones, G.**, **Vigouroux, N.** and Gauthier, P.-J., 2018. Melt inclusion evidence for long term steady-state volcanism at Las Sierras-Masaya volcano, Nicaragua. *Journal of Volcanology and Geothermal Research*, Accepted.
- Lowenstern, J.B., van Hinsberg, V., **Berlo, K.**, Liesegang, M., Iacovino, K., Bindeman, I.N. and Wright, H.M., 2018. Opal-A in Glassy Pumice, Acid Alteration, and the 1817 Phreatomagmatic Eruption at Kawah Ijen (Java), Indonesia. *Frontiers in Earth Science*, *6*, p.11.
- **Stix, J.**, Lucic, G. and Malowany, K., 2017. Near real-time field measurements of δ13C in CO2 from volcanoes. *Bulletin of Volcanology*, *79*(8), p.62.
- van Hinsberg, V., **Vigouroux, N.**, Palmer, S., **Berlo, K.**, Mauri, G., Williams-Jones, A., Mckenzie, J., **Williams-Jones, G.** and Fischer, T., 2017. Element flux to the environment of the passively degassing crater lake-hosting Kawah Ijen volcano, Indonesia, and implications for estimates of the global volcanic flux. *Geological Society, London, Special Publications*, *437*(1), pp.9-34.
- Longpré, M.A., **Stix, J.**, Burkert, C., Hansteen, T. and Kutterolf, S., 2014. Sulfur budget and global climate impact of the AD 1835 eruption of Cosigüina volcano, Nicaragua. *Geophysical Research Letters*, *41*(19), pp.6667-6675.
- Preece, K., Gertisser, R., Barclay, J., **Berlo, K.** and Herd, R.A., 2014. Pre-and syn-eruptive degassing and crystallisation processes of the 2010 and 2006 eruptions of Merapi volcano, Indonesia. *Contributions to Mineralogy and Petrology*, *168*(4), p.1061.

1.1.5. Experimental

The experimental labs at the University of Victoria (Dante Canil and Laurence Coogan) and the University of British Columbia (Mark Jellinek and Kelly Russell) have continued to produce outstanding research in the fields of fluid mechanics, melt rheology and element partitioning as they apply to volcanology/magmatism.

- Aubry, T.J. and **Jellinek, A.M.**, 2018. New insights on entrainment and condensation in volcanic plumes: Constraints from independent observations of explosive eruptions and implications for assessing their impacts. *Earth and Planetary Science Letters*, *490*, pp.132-142.
- D'Souza, R.J. and **Canil, D.**, 2018. The partitioning of chalcophile elements between sediment melts and fluids at 3 GPa, 950–1050° C with implications for slab fluids in subduction zones. *Earth and Planetary Science Letters*, *498*, pp.215-225.
- D'Souza, R.J. and **Canil, D.**, 2018. Effect of alkalinity on sulfur concentration at sulfide saturation in hydrous basaltic andesite to shoshonite melts at 1270 C and 1 GPa. *American Mineralogist: Journal of Earth and Planetary Materials*, *103*(7), pp.1030-1043.
- Giordano, D. and **Russell, J.K.**, 2018. Towards a structural model for the viscosity of geological melts. *Earth and Planetary Science Letters*, *501*, pp.202-212.
- Liao, Y., Bercovici, D. and **Jellinek, M.**, 2018. Magma wagging and whirling in volcanic conduits. *Journal of Volcanology and Geothermal Research*, *351*, pp.57-74.
- Scholtysik, R. and **Canil, D.**, 2018. Condensation behaviour of volatile trace metals in laboratory benchtop fumarole experiments. *Chemical Geology*, *492*, pp.49-58.
- **Schmidt, M.E.**, Perrett, G.M., Bray, S.L., Bradley, N.J., Lee, R.E., Berger, J.A., Campbell, J.L., Ly, C., Squyres, S.W. and Tesselaar, D., 2018. Dusty Rocks in Gale Crater: Assessing Areal Coverage and Separating Dust and Rock Contributions in APXS Analyses. *Journal of Geophysical Research: Planets*, *123*(7), pp.1649-1673.
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- Voigt, M., **Coogan, L.A.** and von der Handt, A., 2017. Experimental investigation of the stability of clinopyroxene in mid-ocean ridge basalts: The role of Cr and Ca/Al. *Lithos*, *274*, pp.240-253.
- Berger, J.A., **Schmidt, M.E.**, Gellert, R., Campbell, J.L., King, P.L., Flemming, R.L., Ming, D.W., Clark, B.C., Pradler, I., VanBommel, S.J. and Minitti, M.E., 2016. A global Mars dust composition refined by the Alpha-Particle X-ray Spectrometer in Gale Crater. *Geophysical Research Letters*, *43*(1), pp.67-75.
- Jessop, D.E., Gilchrist, J., **Jellinek, A.M.** and Roche, O., 2016. Are eruptions from linear fissures and caldera ring dykes more likely to produce pyroclastic flows?. *Earth and Planetary Science Letters*, *454*, pp.142-153.
- Ryan, A.G., **Russell, J.K.**, Nichols, A.R., Hess, K.U. and Porritt, L.A., 2015. Experiments and models on H2O retrograde solubility in volcanic systems. *American Mineralogist*, *100*(4), pp.774-786.

1.1.6. Magmatism and Ore deposits

The link between magmatic systems and ore deposits is well known and Canadian researchers have been advancing our understanding of the interactions between magmas, their fluids and the surrounding crust to produce various types of deposits. Olivier Nadeau at the University of Ottawa and colleagues past and present at McGill University (Kim Berlo, John Stix) and the Université du Québec à Montréal have been active. Pierre Simon Ross (INRS), Michelle DeWolfe (Mount Royal) and Harold Gibson (Laurentian) have also made substantial advances in understanding the formation of economically important Volcanic Massive Sulphide deposits.

- Debreil, J.A., **Ross, P.S.** and Mercier-Langevin, P., 2018. The Matagami District, Abitibi Greenstone Belt, Canada: Volcanic Controls on Archean Volcanogenic Massive Sulfide Deposits Associated with Voluminous Felsic Volcanism. *Economic Geology*, *113*(4), pp.891-910.
- **DeWolfe, Y.M.**, **Gibson, H.L.** and Richardson, D., 2018. 3D reconstruction of volcanic and ore-forming environments of a giant VMS system: A case study from the Kidd Creek Mine, Canada. *Ore Geology Reviews*, *101*, pp.532-555.
- **Nadeau, O.**, Stevenson, R. and Jébrak, M., 2018. Interaction of mantle magmas and fluids with crustal fluids at the 1894Ma Montviel alkaline-carbonatite complex, Canada: Insights from metasomatic and hydrothermal carbonates. *Lithos*, *296*, pp.563-579.
- du Bray, E.A., John, D.A., **Cousens, B.L.**, Hayden, L.A. and Vikre, P.G., 2016. Geochemistry, petrologic evolution, and ore deposits of the Miocene Bodie Hills Volcanic Field, California and Nevada. *American Mineralogist*, *101*(3), pp.644-677.
- Lafrance, B., **Gibson, H.L.**, Pehrsson, S., Schetselaar, E., **DeWolfe, Y.M.** and Lewis, D., 2016. Structural reconstruction of the Flin Flon volcanogenic massive sulfide mining district, Saskatchewan and Manitoba, Canada. *Economic Geology*, *111*(4), pp.849-875.
- **Nadeau, O., Stix, J.** and Williams-Jones, A.E., 2016. Links between arc volcanoes and porphyry-epithermal ore deposits. *Geology*, *44*(1), pp.11-14.
- **Nadeau, O.**, Stevenson, R. and Jébrak, M., 2016. Evolution of Montviel alkaline–carbonatite complex by coupled fractional crystallization, fluid mixing and metasomatism—part I: Petrography and geochemistry of metasomatic aegirine–augite and biotite: Implications for REE–Nb mineralization. *Ore Geology Reviews*, *72*, pp.1143-1162.
- Van Hinsberg, V.J., **Berlo, K.**, Migdisov, A.A. and Williams-Jones, A.E., 2016. CO2-fluxing collapses metal mobility in magmatic vapour. *Geochemical Perspectives Letters*, *824*.
- **Nadeau, O.**, 2015. Economic geology: Ore metals beneath volcanoes. *Nature Geoscience*, *8*(3), p.168.
- **Berlo, K.**, van Hinsberg, V.J., **Vigouroux, N.,** Gagnon, J.E. and Williams-Jones, A.E., 2014. Sulfide breakdown controls metal signature in volcanic gas at Kawah Ijen volcano, Indonesia. *Chemical Geology*, *371*, pp.115-127.
- **Nadeau, O.,** Stevenson, R. and Jébrak, M., 2014. The Archean magmatic-hydrothermal system of Lac Shortt (Au-REE), Abitibi, Canada: insights from carbonate fingerprinting. *Chemical Geology*, *387*, pp.144-156.
- Rogers, R., **Ross, P.S.**, Goutier, J. and Mercier-Langevin, P., 2014. Using physical volcanology, chemical stratigraphy, and pyrite geochemistry for volcanogenic massive sulfide exploration: An example from the Blake River Group, Abitibi Greenstone Belt. *Economic Geology*, *109*(1), pp.61-88.

- Yılmazer, E., Güleç, N., Kuşcu, İ. and **Lentz, D.R.**, 2014. Geology, geochemistry, and geochronology of Fe-oxide Cu (±Au) mineralization associated with Şamlı pluton, western Turkey. *Ore Geology Reviews*, *57*, pp.191-215.

2. Research Institutions and Personnel

Research in Canada is concentrated within the university and college community including: Brock University, Carleton University, Douglas College, the Institut National de la Recherche Scientifique, Laurentian University, McGill University, Mount Royal University, Quest University, Simon Fraser University, University of Alberta, University of British Columbia, University of New Brunswick, University of Ottawa, University of Quebec at Chicoutimi, University of Regina, and University of Victoria. Research is also conducted by a small group of scientists within Natural Resources Canada.

All together, there are about 25 faculty and research scientists at Canadian universities carrying out IAVCEI-related research on a wide range of topics. These researchers together supervised approximately 118 MSc, PhD and postdoctoral fellows between 2014 and 2018.

Senior Researchers	M.Sc. students	Ph.D. students	Postdoctoral Fellows
25	49	57	12

3. Major scientific conferences/workshops

Canadian scientists regularly present their research at a broad range of major national and international conferences and workshops including:

2014
- LPSC, Mar. 2014, The Woodlands, TX, USA
- GSA Annual Meeting, June 2014, Vancouver, BC, Canada
- GAC-MAC, June 2014, Fredericton, NB, Canada
- Goldschmidt, June 2014, Sacramento, CA, USA
- IAVCEI Cities on Volcanoes 8, Sept. 2014, Yogiakarta, Indonesia
- AGU Fall Meeting, Dec. 2014, San Francisco, CA, USA

2015
- LPSC, Mar. 2014, The Woodlands, TX, USA
- IAVCEI - IUGG, June 2015, Prague, Checz Republic
- Goldschmidt, Aug 2015, Prague, Checz Republic
- RIMS Canada, Sept 2015, Quebec City, QC, Canada
- GSA Annual Meeting, Nov. 2015, Baltimore, MA, USA
- AGU Fall Meeting, Dec. 2015, San Francisco, CA, USA
- AGU-GAC-MAC-CGU Joint Assembly, May 2015, Montreal, QC, Canada

2016
- LPSC, Mar. 2014, The Woodlands, TX, USA
- PEG, June 2017, Kristiansand, Norway
- GAC-MAC, June 2016, Whitehorse, YT, Canada
- GSA Annual Meeting, Sept. 2016, Denver, CO, USA
- IAVCEI Cities on Volcanoes 9, Nov. 2016, Puerto Varas, Chile
- AGU Fall Meeting, Dec. 2016, San Francisco, CA, US

2017
- LPSC, Mar. 2014, The Woodlands, TX, USA

- EGU General Assembly, Apr. 2017, Vienna, Austria
- CGU, May 2017, Vancouver, BC, Canada
- IAVCEI General Assembly, Aug. 2017, Portland, OR, USA
- Goldschmidt, Aug. 2017, Paris, France
- SGA Biennial Meeting, May 2017, Quebec, QC, Canada
- GSA Annual Meeting, Oct. 2017, Seattle, WA, USA
- AGU Fall Meeting, Dec. 2016, New Orleans, LA, USA

2018
- AGU Chapman conference, Jan. 2018, Quinamavida, Maule Region, Chile
- NGWM, Jan. 2018, Copenhagen, Denmark
- EGU General Assembly, Apr. 2018, Vienna, Austria
- Maar Conference, May 2018, Olot, Catalonia, Spain
- Resources for Future Generations, June 2018, Vancouver, BC, Canada.
- INQUA-INTAV, June 2018, Moieciu de Sus, Romania
- Goldschmidt, Aug. 2018, Boston, MA, USA
- GSA Annual Meeting, Nov. 2018, Indianapolis, IN, USA
- IAVCEI Cities on Volcanoes 10, Sept. 2018, Naples, Italy
- AGU Fall Meeting, Dec. 2018, Washington, D.C., USA

4. Major awards

Three Canadian researchers, Profs Don Baker (McGill), Dante Canil (UVic) and Derek Thorkelson (SFU) received major national and international awards in recognition of their scientific contributions.

2014
- Peacock Award, Mineralogical Association of Canada
- Fellow, Mineralogical Association of Canada

2015
- Fellow, Geological Society of America

2016
- NL Bowen Award, American Geophysical Union
- Fellow, Mineralogical Association of Canada

2018
- Howard Street Robinson Medal, Geological Association of Canada

5. Major Challenges for Research

5.1. Recognition and collaboration

As mentioned earlier, the limited recognition by governments and the public that volcanoes are a potential threat and natural hazard within Canada is a hurdle we as a community continue to find challenging. The lack of federal and provincial funding for basic geological/volcanological mapping, geochronological dating and monitoring of these potentially hazards volcanic centres is a result of this limited understanding and perpetuates the status quo. In spite of the long history and economic importance of mineral resources in Canada, there is still only a passing understanding of the importance of fundamental research in volcanology and magmatic systems to the minerals and energy (geothermal) sector.

There is currently insufficient collaboration within the community between those studying modern volcanic systems and those working primarily on ancient systems. There appears to be a broader bias in the international volcanological community that "*your research is not really volcanology, because your rocks are too old*".

The relatively small number of researchers covering a broad research discipline means that there is not the critical mass necessary to effectively promote the field and as such only a limited number of interested domestic students with strong backgrounds in chemistry and physics apply. At most institutions, effective recruiting of overseas graduate applicants is hindered by high international student fees; this could be alleviated by institutionally-supported foreign tuition waivers.

5.2. Funding

The lack of broader funding for fundamental scientific research and student support often makes it difficult to ensure graduate students complete their theses in a timely fashion (many students are forced to work in industry during the summer) and publish their research after the thesis is completed. In the current NSERC Discovery assessment model, the emphasis on HQP (highly qualified personnel) training and expectation of a large number of students is not matched by the limited financial support for HQP and as such impacts negatively on grant success rates. While many researchers can find in-kind support from national and international collaborators, the major issues are still HQP salaries and analytical/field costs.

Nationally, there is limited access to basic analytical facilities (e.g., microprobe, LA-ICPMS, etc.) and where it exists, it is typically aging. There are only a limited number of “targeted” funding mechanisms to replace and upgrade this research infrastructure (e.g., CFI, NSERC RTI) and virtually no support for maintenance or operation. This is particularly problematic for researchers at smaller universities and colleges.

There has also been a tendency over the last decade to prioritize funding programs that focused on industry collaboration (e.g., NSERC CRD, Mitacs) with the limited number of non-industry programs still being thematically targeted. There is clearly a need to support medium to large-scale research projects similar to, and ideally in collaboration with, programs in the NSF, NERC or EU.

There is, however, cause for cautious optimism given some recently announced initiatives such as the Tri-Agency Fund.

6. Brief summary of achievements

In spite of the significant difficulties faced by Canadian researchers due to funding and infrastructure issues, the community has made significant contributions in a wide range of themes to the broader scientific community.

Examples of this includes the novel application of Quaternary glaciovolcanism in the Canadian Cascades to understand paleoenvironmental conditions; new experimental constraints on the viscosity of geological melts and the contribution of sulphides to the stability of subduction-zone melts; 3D characterisation of large scale modern magmatic systems in the Andes and ancient bodies in Canada associated with giant VMS deposits.

The quality of Canadian researchers is further exemplified by the fact that during 2014-2018, three of our colleagues received significant national and international awards for their scientific contributions.

Section 8 International Association of Cryospheric Sciences (IACS)

2015-2018 Quadrennial Report

SECTION A: Sea Ice
SECTION B: Glaciers and Ice Sheets
SECTION C: Seasonal Snow
SECTION D: Permafrost
SECTION E: Lakes and Rivers
SECTION F: Cryospheric Data Management and Archive

SECTION A: SEA ICE

Report compiled by Randy Scharien, University of Victoria

The report is divided into 6 sections, based on the following institutions that have provided input for this report:

- C-CORE, Memorial University of Newfoundland
- University of Calgary, Department of Geography
- University of Victoria, Department of Geography
- Institut national de la recherche scientifique, Centre Eau Terre Environnement
- University of Manitoba, Department of Geological Sciences
- University of Manitoba, Department of Electrical and Computer Engineering

1 C-CORE, Memorial University of Newfoundland (Desmond Power)

1.1 Maritime surveillance

C-CORE has been working with Defence R&D Canada on ship and iceberg detection algorithms for C-Band Synthetic Aperture Radar. These have concentrated on various modes of RADARSAT-2 and RADARSAT Constellation Mission. Efforts have focused on what can be achieved in detection performance in open water conditions and within sea ice. With respect to polarization, C-CORE's research has shown that multi-polarization increases the probability of detection, with quad polarization has the highest performance. RADARSAT Constellation Mission contains a dual polarization mode called Compact Polarimetry (CP) where circularly polarized waves are transmitted and horizontal and vertical polarized waves are received. This mode is shown to be more effective than traditional dual polarization modes and approaches quad-polarization in its performance. (Power et al. 2018; Zakharov et al. 2016; Power et al. 2016, 2017).

1.2 Deep learning of Synthetic Aperture Radar (SAR)

Deep learning techniques have become popular thanks to the development and advancement of graphical processing units (GPUs) for solving computationally intensive tasks. One such deep learning technique, Convolution Neural Networks (CNN), uses feed-forward artificial neural networks and is commonly applied to analyzing imagery. C-CORE has applied these techniques to the ship and iceberg discrimination problem. C-CORE has received support from both DRDC and Equinor for these activities and have so far concentrated on C-Band SAR from Sentinel-1. Standard computer vision techniques result in SAR classifier accuracies of between 85%-95%, depending on the resolution of the SAR and the availability of multiple polarizations. CNN-based algorithms produced an improved classifier improving accuracy by approximately 5%. These techniques typically require thousands of samples to properly train the algorithms. C-CORE is presently working on applying these techniques to CP mode SAR data, simulated from RADARSAT-2. Results should be available in late 2019 and will be presented at future symposia (Power et al. 2018).

1.3 Backscatter modelling of icebergs at C-band frequency

We have been developing a C-Band backscatter model for icebergs at C-Band that would allow us to simulate backscatter from icebergs in various C-Band SARs. So far, our research has produced effective models for Sentinel-1 and RADARSAT-2. Comparisons between the model and SAR data collected over Bonavista, NL, have been promising. The associated fieldwork has involved capturing of 3D profiles of icebergs (sonar and lidar) during the time of SAR data acquisition. The 3D profiles allow us to do full 3D electromagnetic modelling of icebergs at C-band (Ferdous et al. 2018; Ferdous 2018; Himi 2018).

1.4 Sea ice modelling

The aim of this research is to retrieve sea ice parameters by the fusion of a high-resolution sea ice model and remote sensing data. We have implemented and developed a regional standalone (uncoupled) sea-ice model for the region of Baffin Bay, Hudson Bay and the Labrador Sea. The model was tested for numerical stability and sensitivity to atmospheric inputs. Moreover, it has data assimilation frame work developed into it, which improves model estimates of ice concentration, thickness and freeboard. The existing assimilated sea-ice models use a constant drag formulation for the representation of the heat exchange between ice and the water below while the newly implemented model uses a variable drag formulation in the assimilation scheme to update the heat exchange and also provides estimates of sea ice parameters such as, sail height and keel depth. A novel method was also introduced to estimate the level ice draft and the keel depth from upward looking sonar

(ULS) measurements, which were then compared with the model predicted values to determine the relationship between the sail and keel depth of sea ice floes (Prasad et al. 2016; Prasad, Zakharov, and Bobby 2016; Prasad et al. 2015).

1.5 Detection of icebergs in sea ice using InSAR technology

An important applied problem of monitoring icebergs in sea ice was solved using interferometric synthetic aperture radar (InSAR) technology. The advantages of using an interferometric method for detecting and characterizing icebergs in sea ice were demonstrated (Zakharov et al. 2019). Iceberg topography was analyzed using single-pass TanDEM-X InSAR data. InSAR processing was used to extract 3-D elevation information of the sea ice surface (Zakharov, Power, et al. 2017). The results firmly demonstrate the capability of TanDEM-X data to characterize the shape of icebergs. Very high resolution (VHR) optical satellite data were collected by Pleiades 1A over the same area as InSAR data to derive digital elevation models (DEMs) of ice features for validation. The quantitative comparison demonstrated good correspondence between InSAR and optical DEMs. Using optical imagery for validation, it was also possible to calculate receiver operating characteristics (ROC) for detecting icebergs in sea using InSAR. The resulting ROC analysis illustrates a good detection performance, comparable to detection of icebergs in open water. The results can potentially be used with tandem satellite missions or airborne sensors.

1.6 Validation of radar altimetry method for iceberg detection and ship-iceberg classification

Recent research has confirmed that satellite radar altimetry can be used for detecting icebergs. In an effort to validate the altimetry-based approach, the study (Zakharov, Puestow, et al. 2017) was conducted using 105 samples of icebergs contained in both satellite altimeter data and ENVISAT-ASAR scenes for the Weddell Sea area. The probability of detecting icebergs larger than 150 m waterline-length was 47%. The problem of discriminating ships and icebergs based on altimeter measurements was addressed using an ensemble of automated classifiers. A total of ten features were defined from the altimetry signal to be used as predictor variables in supervised classification. The classifier ensemble comprised discriminant functions, k-nearest neighbor, neural networks, support vector machines, and decision tree analysis. Several algorithms successfully classified objects as ships or icebergs with an accuracy exceeding 85%.

1.7 Satellite-Based Monitoring of River Ice

C-CORE in collaboration with several other Canadian partners has performed a body of research on river ice monitoring with SAR. Flooding due to ice jams is a major and frequent hazard for communities located near rivers in cold and northern regions of the world. Ice jams might be formed during the development of ice covers in early winter or during ice cover break up in early spring. A related issue is the management of river flows on regulated rivers, especially the routing of early spring runoff during ice conditions while minimizing the risk of initiating ice jams. Flood forecasting for such rivers is challenging due to the complexities of modelling ice formation and breakup in real-time in an operational context. It is further complicated by the effect of climate change, which has changed historically observed ice cover formation behavior.

C-CORE has developed and implemented an operational river ice monitoring capability based on SAR imagery to address the challenges of flood forecasting, river flow management and climate change adaptation. Initially developed and implemented for the Town of Badger on the island of Newfoundland, Canada, following a severe river ice induced flood in 2003, the satellite-based service is provided to communities at risk across Canada. Satellite-based river ice monitoring initially relied on the use of satellite RADAR imagery from the ENVISAT, RADARSAT 1 and RADARSAT-2 but has since moved onto include Sentinel-1 and X-band SAR. (Warren et al. 2017; Puestow et al. 2017; Khan and Puestow, 2015; Puestow and Khan 2015)

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2 Department of Geography, University of Calgary (Dr. John Yackel)

2.1 Arctic snow on sea ice thermodynamics

Research focused on understanding the role of thermodynamic processes involved the growth, evolution and decay of Arctic sea ice aimed at understanding the response of Arctic sea ice to climate change. Paramount to this is understanding the complex roles of direct and indirect effects of the snow cover on sea ice thermodynamics. Specific research includes the use of surface and satellite-based multifrequency and polarimetric microwave remote sensing systems to invert snow cover and sea ice melt stage properties and processes. Methods approach involves field, laboratory-based and numerical modelling activities.

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3 Department of Geography, University of Victoria (Randy Scharien)

3.1 Sea ice melt information retrieval from synthetic aperture radar

This research focuses on advancing the measurement capability of C- and L-band frequency synthetic aperture radar (SAR) for discriminating melting stage and ice types during the spring/summer melting period. From 2015-2018, SAR images were collected over dedicated sites in the Canadian Arctic Archipelago; a field site on first-year sea ice in Dease Strait, accessible from the Canadian High Arctic Research Station (CHARS) in Cambridge Bay, and a site of key interest containing first-year and multiyear ice, accessible by aircraft only. A technique was developed to estimate the spring melt pond fraction of first-year and multiyear ice types using HH-polarization backscatter from the C-band frequency Sentinel-1 SAR mission collected during the winter (pre-melt) period. The method provides seasonal maps demonstrating the pre-conditioning of the sea ice surface for thermodynamic melt. It is being used to investigate enhanced summer sea ice area minimum forecasting. Fully-polarimetric RADARSAT-2 images were collected and used to simulate the compact polarimetric parameters (CP) and imaging modes of pending RADARSAT Constellation Mission. Optimal simulated CP parameters for discriminating first-year and multiyear ice types during winter and advanced melt conditions, and for deriving information on the seasonal evolution of sea ice (i.e. phenology) were investigated.

3.2 Regional-scale sea ice structure and seasonal evolution

High-resolution airborne surveys of sea ice were used to evaluate the winter (pre-melt) controls on spring melt pond fraction and ice melting rates. This investigation was motivated by the need to better understand the surface contribution to the overall controls (surface, lateral, and bottom) on seasonal melting rates of sea ice in the Canadian Arctic Archipelago. In April 2015, and April 2016, through collaboration with York University and

Environment and Climate Change Canada (ECCC), airborne surveys of winter period sea ice thickness from EM-induction, and sea ice roughness from a Riegel Q120 laser measurement system, were conducted along transect lines in the M'Clinotck Channel and Victoria Strait portions of the Canadian Arctic Archipelago. High-resolution optical images (in 2015) and a repeat airborne survey with and optical imaging system (in 2016) provided data for partitioning relative sea ice, open water, and melt pond fractions. Surface constraints on sea ice melt pond fraction evolution were determined and a model for estimating spring pond fraction from winter sea ice thickness was provided. Data sets are being used to investigate the role of surface roughness on simulated satellite altimeter waveforms, and for understanding altimeter based thickness estimation errors.

3.3 In situ snow and sea ice geophysics and effects on microwave backscatter

Through collaboration with University of Manitoba, ice tank based studies of the temperature and salinity evolution of sea ice coincident to C-band frequency normalized radar cross-section data were made. An inversion algorithm for reconstructing the time evolution of sea ice salinity and temperature using single-frequency time-series radar cross-section data was demonstrated. The technique assumes that the temperature and salinity profiles are initially known with sufficient accuracy.

Study of the effects of seasonally evolving snow geophysics on satellite radar altimeter waveforms and waveform based ice thickness estimates was undertaken. Investigation was made of upward brine migration in snow overlying saline first-year sea ice in Dease Strait in the Canadian Arctic Archipelago. Snow salinity and other geophysical measurements (density, grain size, temperature) were used to calculate the depth of maximum return power within the snow layer, at radar altimeter frequencies Ku- and Ka-band. Data are being used to assess sea ice thickness retrieval errors for first-year sea ice, which currently rely on the assumption of snow transparency at the Ku-band frequency. Maximum power returns from within the snow lead to sea ice thickness overestimations at Ku-band.

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4 Institut national de la recherche scientifique, Centre Eau Terre Environnement (Monique Bernier)

4.1 IceMap250 and IcePAC: Development of tools to monitor sea ice conditions in Hudson Bay

Reliable knowledge and assessment of sea ice conditions and their evolution over time is a priority for many decision makers. With this in mind, a mapping tool and a probabilistic model, respectively called IceMap250 and IcePAC (Gignac et al. 2017; Gignac, Bernier, and Chokmani 2019), were developed. The first tool uses 250m downscaled MODIS data to map sea ice presence in the Hudson Bay with an overall Kappa value over 0.9 for all seasons. The second tool uses using frequency modeling of time series of ice concentrations (1978-2015) derived from passive microwave remote sensing data for the Hudson Bay area. Results show that it is possible to evaluate the probabilities of events such as the shortest / longest duration of the ice-free season and the probabilities of different melting and freezing dates all over the study area. This modelling framework can be transposed to other datasets as well as to other study areas.

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5 University of Manitoba, Department of Geological Sciences (Søren Rysgaard)

5.1 Ice tank studies

We established the Sea ice Environmental Research Facility (SERF) on the University of Manitoba campus and showed that it is possible to grow sea ice under experimental conditions and to produce different forms of sea ice, new forming sea ice with and without frost flowers, pancake ice, various forms and thickness of fast ice (Geilfus et al., 2016; Galley et al., 2015). In addition, we have showed that oxygen and carbon dioxide is being rejected to the underlying water and that calcium carbonates in the form of ikaite are produced within hours after ice formation (Else et al., 2015). A new technique has also been developed to image brine channels and pockets in young sea ice in three-dimensions using a magnetic resonance (Galley et al., 2015). My team is also behind a new technique making it possible to quantify the gas volume in intact sea ice cores using non-destructive x-ray tomography (Crabeck et al., 2016). This will greatly improve our understanding gas exchange over sea ice interfaces, something that is important for understanding the greenhouse gas exchange between high latitude seas and the atmosphere.

5.2 In situ sea ice and carbon cycling

The role of ice-covered oceans in the air–sea CO2 exchange has been largely ignored because sea ice is assumed to impede gas exchange with the atmosphere. Using the experimental data obtained from SERF to plan our in situ studies my team has changed that assumption and shown that physical and chemical processes in the sea ice act as an important control on pH and CO2 levels of the sea surface and thus the air–sea exchange and acidification state of surface waters in the Arctic (Sievers et al., 2015). Results from our studies demonstrate the importance of community respiration on spring productivity, as respiration rates can maintain a heterotrophic state independent of algal growth. This challenges previous assumptions of a fully autotrophic sea ice community during the ice-covered spring (Campbell et al., 2017).

5.3 Polynyas

Polynyas are an important yet poorly understood phenomena of high latitude oceans. Polynyas are areas of open water surrounded by sea ice. A question is what the role of a polynya play in the exchange of energy, brines and greenhouse gas fluxes. My team has shown that storm events with down-fjord winds of up to 25 m/s can force the collapse of landfast ice on the coastal shelf. The storm created a coastal polynya that was further maintained by several consecutive wind events over several months. The polynya generated sufficient amount of brine to ventilate the interior of a fjord (Dmitrenko et al., 2015; Boone et al., 2017; Kirillov et al., 2015). When sea ice produced in the polynya melts elsewhere it lowers the surface water partial pressure of CO2 and increases the air-sea CO2 flux (Sievers et al., 2015). Thus, as climate is warming in the Arctic, thinner sea ice may result in more polynyas and their influence on water mass structure, nutrient upwelling and greenhouse gas exchange may increase. This is expected to affect sea ice algal communities with cascading effects to higher trophic levels and eventually fisheries.

5.4 Productivity and CO_2 dynamics in coastal systems

The melting of tidewater outlet glaciers from ice sheets contributes significantly to global sea level rise. Although accelerated mass loss is related to melt processes in front of calving glaciers the role of ocean heat transports is poorly understood. My team has presented the first direct measurements from a subglacial plume in front of a calving tidewater outlet glacier of the Greenland Ice Sheet (Bendtsen et al., 2015a). Surface salinity in the plume corresponded to a meltwater content of 7%, which is indicative of significant entrainment of warm bottom water and, according to plume model calculations, significant ice melt (Bendtsen et al., 2015b). We have shown a complex interplay between glacier thinning, runoff, surface mass balance, ocean conditions, submarine melting, bed topography, ice mélange and that sea ice conditions may also affect glaciers (Motyka et al., 2017; Bendtsen et al., 2017). Finally, my team has for the first time shown that this greatly stimulates primary production through upwelling of nutrients from subsurface layers in front of glaciers (Meire et al., 2017; Meire et al., 2016). This melt-water release is responsible for a second large plankton bloom period in addition to the classic spring bloom (Juul-Pedersen et al., 2015). The melt water discharge is also responsible for a year-round CO2 undersaturation of surface waters in the entire fjord and adjacent continental shelf (Meire et al., 2015).

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6 University of Manitoba, Department of Electrical and Computer Engineering (Dustin Isleifson)

6.1 Microwave remote sensing and antenna design

Efforts include remote sensing experimentation, antenna design, and field work in Arctic regions (ArcticNet, CCGS Amundsen programs), with primary research objectives to link to technology development to practical applications that will be meaningful for Arctic research. Major contributions to sea ice research in the 2015-2018 timeframe have included: (i) remote sensing (passive microwave and drone surveys) and sea ice characterization onboard the CCGS Amundsen, as part of the BaySys project [3, 5]; (ii) experiments on artificial sea ice at the Sea-ice Environmental Research Facility (SERF) [4, 6]; and (iii) oil spill detection in sea ice environments (measurement and modeling studies) [1, 2].

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SECTION B: GLACIER AND ICE SHEETS

Report compiled by Shawn Marshall, University of Calgary

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1. Research Highlights, 2015-2019

Canadian glacier, ice sheet, and ice shelf research includes field and modelling efforts in western and Arctic Canada, Greenland, and Antarctica. Research based out of the Universities and Natural Resources Canada included the training of over 40 graduate students from 2015-2019 (14 PhD and 27 MSc graduates over this period). A detailed list of projects and study sites is included in Section 3, following a brief summary of research highlights and technological developments reported by the national community.

Glacier Dynamics

Research at Simon Fraser University (SFU) and the University of British Columbia (UBC), includes studies of surging glacier dynamics in Yukon Territory. In a study of 16 glacierized basins in the St. Elias Mountains of Yukon, Crompton et al. (2018) report a statistical association between bedrock fracture characteristics and the propensity for glaciers to surge (or exhibit unstable flow behaviour). This finding leads to a new hypothesis for the underlying cause of surging, relating bedrock fracture characteristics to the friction imparted by clasts at the glacier bed. Modelling of surging glacier dynamics at UBC has created the first models of glacier structural evolution during surge cycles (Clarke and Hambrey, 2019; Hambrey and Clarke, 2019). Research at the University of Lethbridge is also examining glacier structure and interactions between ice dynamics and valley morphology (Jiskoot et al., 2017).

Remote-sensing efforts led out of University of Ottawa led to the first complete velocity maps for all glaciers and ice caps in the Canadian Arctic, as well as major glaciers of western Canada (Van Wychen et al., 2018). The Arctic results demonstrate that White Glacier on Axel Heiberg Island and Penny Ice Cap on Baffin Island have both experienced long-term reductions in surface velocity in response to negative mass balance conditions (Gilbert et al., 2016; Thomson and Copland, 2017). Remote sensing and modelling studies of marine-terminating outlet glaciers on Devon Island provides additional insight into the dynamics of Canadian Arctic ice masses (Van Wychen et al., 2017; Pimental et al., 2018).

Glacier velocities and surface temperatures have also been successfully mapped by AUVs (Kraaijenbrink et al., 2016, 2018), in research led by Joe Shea of the Kathmandu-based International Centre for Integrated Mountain Development (ICIMOD). Shea is now at the University of Northern British Columbia (UNBC).

Glacier Modelling

Numerical models of glacier and ice sheet dynamics are under development at SFU, UBC, the University of Calgary, Memorial University, and the University of Waterloo, with applications to paleo ice sheets, Arctic Canada and Greenland, and the historical and future evolution of mountain glaciers. Garry Clarke's group at UBC advanced the state of mountain glacier modelling through the introduction of a regional glaciation model (RGM) which explicitly resolves glacier evolution on mountain-range to continental scales. An ambitious application to western Canada involved simulations of more than 20,000 western Canadian glaciers under an ensemble of 21st-century climate-change scenarios (Clarke et al., 2015). Additional applications of the RGM include a study led out of UNBC examining the timing and processes of Cordilleran Ice Sheet deglaciation (Menounos et al., 2017).

Models of glacier dynamics and subglacial hydrology at SFU (Flowers, 2015) and Waterloo have also been developed to examine glacier flow processes in Arctic Canada, Greenland, and Antarctica (e.g., Gilbert et al., 2016; Dow et al., 2018; Pimental et al., 2018), while more simplified flowband models of ice dynamics are under development in Calgary for studies of the Columbia Icefield and for interactive coupling with climate models. A UBC-led study also explored the application of simplified scaling models of glacier geometric evolution in global-scale studies of glacier response to climate change (Bach et al., 2018).

Glaciological models require accurate climate forcing. This is a large challenge for modelling of mountain glacier mass balance, and research at UBC, UNBC, the Pacific Climate Impacts Consortium (PCIC), and the Universities of Calgary, Alberta, and Québec (UQAM) is focused on developing downscaling strategies for meteorological forcing from climate models. The UNBC group completed six years of high resolution (1-km) regional climate modelling in the Columbia River Basin using the WRF model, complementing LiDAR- and ground-based glacier mass balance studies in the region (Pelto et al., submitted). UBC and PCIC work includes downscaling of global climate model data for regional to global glacier mass balance modelling (e.g., Clarke et al., 2015), while research in Calgary and at UQAM is developing strategies to embed glacier mass balance models within regional climate models (Perroud et al., 2019).

Ice Shelf Processes

Ice shelves and ice islands were a major focus in Canadian glaciology over the last several years, including publication of the first dedicated book on Arctic Ice Shelves (Copland and Mueller, 2017). Research led out of Carleton University created a geospatial database that documents the drift and deterioration of ice islands originating from the Petermann and other glaciers in northwestern Greenland. The Canadian Ice Island Drift, Deterioration and Detection (CI2D3) Database (available online from the Polar Data Catalogue) includes 25,000 polygons of ice islands that were digitized from satellite imagery. Crawford et al. (2019) describe ice island fragmentation processes and meltwater production from Petermann Glacier calving events.

The breakup of Canadian Arctic ice shelves was shown to be linked to declines in the presence of protective multiyear landfast sea ice at their margins, together with thinning driven by warming air temperatures (Cook et al., 2019). Similar processes are also impacting epifaunal lakes on Arctic ice shelves, with interactions between lake extent and ice-shelf thickness (Hamilton et al., 2017).

On a larger scale, Dow et al. (2018) show that Antarctic and Greenland ice shelf transverse fractures are linked to the location of basal ice shelf channels, which can lead to large calving events. The locations of ice shelf surface rivers are also driven by the hydrostatic imbalance due to the basal channels and could exacerbate rifting when they flow into the transverse fractures. A case study site, Nansen Ice Shelf, demonstrates the shelf strain conditions that allow transverse fractures over the thinnest ice of the basal channels. These fractures were also identified at highly sensitive sites including Pine Island Glacier and Petermann ice shelves.

Glacier Mass Balance

The Canadian glaciological community contributes to glacier mass balance studies on several fronts, including longterm monitoring efforts led by Natural Resources Canada (NRCan) and Trent/Queen's University, mass balance process studies in various research groups, and remote sensing studies of glacier change out of NRCan, the Canadian Centre for Remote Sensing, University of Ottawa, University of Alberta, and UNBC. CryoSat-2 radar altimeter satellite data is now been integrated directly in the NRCan glacier monitoring and assessment program (Gray et al., 2015). The University of Ottawa and Queen's groups integrated some of these methods through structure-from-motion analyses (Thomson and Copland, 2016) and a long-term reanalysis of glaciological vs. geodetic mass balance at White Glacier, Axel Heiberg Island (Thomson et al., 2018).

The NRCan, Queen's, and Alberta groups contributed to recent synthesis reports on Arctic glacier change (Box et al., 2018), while UNBC was involved in an international synthesis report on status and change of the cryosphere in High Mountain Asia (Bolch et al., in press). Land ice and the broader cryosphere are responding dramatically to recent climate warming in both regions. Remote sensing studies in Arctic Canada indicate that glaciers across northern Ellesmere Island decreased in area by more than 1700 km^2 (6%) between 1999 and 2015, while ice cap thinning is widespread (Mortimer et al., 2018). There is darkening of the ablation zones associated with intense melt years (Mortimer and Sharp, 2017), particularly in association with increased advection of warm, humid air masses into the region of Baffin Bay and southwestern Greenland.

Through efforts led out of UNBC, glacier monitoring efforts in western Canada have increased over the past decade, including the initiation of seasonal mass balance measurements at several new glaciers in the Columbia River Basin of southeastern British Columbia (Zillmer, Nordic, Conrad, Kokanee, and Illecillewaet). Ice thickness data has been collected at these sites and repeat airborne LiDAR conducted since 2014 (Menounos et al., 2018) complements the field data and offers a detailed comparison between geodetic and glaciological mass balance estimates (Pelto et al., submitted). On a larger scale, remote-sensing studies provide the first comprehensive estimates of glacier mass change for western Canadian glaciers (see Menounos et al., 2019). Remote-sensing based methods are also being developed for monitoring of alpine snowpacks (Wayand et al., 2018).

Glacier-Climate Processes

Meteorological variability and climate change have a myriad of influences on glacier energy and mass balance, beyond just the direct effects of changing temperatures. Shifts in Arctic sea ice can impact the snow accumulation regime and sensible heat transfer to ice caps, and changes in coastal fog regime are also occurring, with impacts on the radiation budget. Research at the University of Lethbridge introduces new techniques using radiosonde and weather station data to extract Arctic fog climatology and macrophysical characteristics, to evaluate their influence on glacier surface energy balance (Gilson et al., 2018a,b).

Characterization of turbulent fluxes remains challenging in glacial environments. ICIMOD/UNBC researchers successfully deployed an eddy co-variance system to measure turbulent fluxes at an elevation of 5350 m, providing estimates of the role of sublimation in the mass balance of high-altitude glaciers (Stigter et al., 2018). Collaborative research between UBC and UNBC has led to innovations in modelling of turbulent heat exchange, permitting a physically-based parameterization of the katabatic boundary layer (Radić et al., 2017). Studies based out of the University of Calgary are examining the surface energy balance sensitivity to meteorological variability in the Canadian Rockies, quantifying the effects of changes in wind, humidity, cloud conditions, and radiation fields on incoming longwave radiation and summer melt (Ebrahimi and Marshall, 2015; 2016).

2. Technological Developments

Technological developments continue to shape progress in cryospheric monitoring and process studies. The remote, off-grid nature of glaciers and ice caps demands low-power, light-weight, and portable field instruments. This is fuelling innovations in ice radar, ice-coring, and datalogger systems. Research at SFU and industry collaborator Blue System Integration Ltd. has led to the deployment of stationary ice-penetrating radar (sIPR) systems designed to monitor englacial hydrology. Four deployments of up to three months during the melt seasons of 2014, 2015 and 2017 revealed changes in englacial water storage associated with the filling and drainage of an ice-dammed lake in southwest Yukon. At Carleton University, low-cost dataloggers/Iridium telemeters called Cryologgers (http://cryologger.org) are being developed for use in cold environments. Low-cost satellite trackers have also been employed by the University of Ottawa on approximately 40 icebergs and ice islands across Baffin Bay and Nares Strait.

Satellite measurements are also being increasing employed in glacier monitoring. Research at NRCan includes the development and validation of near real-time monitoring of ice caps in the Canadian Arctic through satellite telemetry and radar altimetry. In western Canada, snow persistence/absence indices to evaluate wind redistribution of snow developed from remotely sensed imagery using Google Earth Engine (Wayand et al. 2018). Unmanned autonomous vehicles (UAVs) are also being deployed effectively in research at UNBC and the University of Calgary, including observations of surface temperatures over debris-covered glaciers (Kraaijenbrink et al., 2018), glacier velocity measurements (Kraaijenbrink et al., 2016), and mapping of supraglacial water channels and canyons on Bylot Island in Arctic Canada (Bash et al., 2018).

Brian Menounos at UNBC received funds from the Canadian Foundation for Innovation and the Tula Foundation (Hakai Institute) to establish an airborne laser altimetry (LiDAR) observational platform to monitor snow and ice in western Canada. Several glaciers in western Canada have being flown and mapped twice a year since 2015 to provide geodetically-derived estimates of glacier mass change, supplementing field-based observations made by the UNBC, NRCan, and University of Calgary. In May, 2019 the LiDAR system will be combined with new equipment and a dedicated aircraft to launch the Airborne Coastal Observatory (ACO), a fully dedicated, dual-port aircraft (Piper Navajo) with crew (four technicians and one manager), LiDAR system, dual 100 Megapixel digital cameras and hyperspectral (0.45-2500 micron) system that will be made available for coastal and snow and ice research for the next 5-10 years. The ACO will have a primary focus in the British Columbia Coastal Mountains, but it is anticipated that the system will be available for other snow and ice research in western Canada.

Bridging satellite remote sensing and surface energy/mass balance processes, research at the University of Lethbridge has led to the development of three novel methods: 1) calculation of fog top height from radiosonde data, 2) automatic classification of Arctic fog types from thermodynamic profiles, and 3) regional classification of fog from MODIS and CALIPSO remote sensing data. This can inform regional-scale Arctic mass balance modelling, where coastal fog is known to suppress low-altitude ablation. Other new techniques in field methods include University of Calgary research to deploy time-domain reflectometry (TDR) sensors in near-surface snow and firn (Samimi and Marshall, 2017). In conjunction with thermistors, vertical profiles of TDR sensors allow direct tracking of meltwater percolation, refreezing, and snow hydraulic properties. This instrumentation was piloted in the Canadian Rockies in 2015. TDR arrays were deployed at Dye2, Greenland in 2016 and 2017, with success in tracing meltwater percolation, thermal evolution, and ice layer development in the near-surface firn.

Innovations in modelling include the development of the regional glaciation model at UBC, noted above. This includes the full suite of technical steps from estimation of ice-free topography through to downscaling of meteorological forcing from climate model reanalyses or projections, orographic precipitation modelling, and two-dimensional ice dynamics. Model resolution in Clarke et al. (2015) is 100 or 250 m, on the scale of western Canada. At the University of Waterloo, the GlaDS hydrological model was adapted to Antarctic applications, including distributed supercooling freeze-on processes and subglacial lake growth and drainage (Dow et al., 2018).

3. Glaciology Research Projects led by Canadian PIs, 2015-2018

David Burgess, Natural Resources Canada (NRCan)

Glacier mass balance monitoring: Assessments of long-term reference glaciers in the Canadian Arctic and western cordillera (ongoing)

Reanalysis of long-term mass balance time series of WGMS reference glaciers in the Canadian Arctic and western cordillera (2017-2020)

Assessment of glacial melt and potential impacts on water resources in the Canadian Rocky Mountains (2016-2019)

Garry Clarke, University of British Columbia

Projected deglaciation of western Canada: Projecting changes in 21st century glacier extent using downscaled GCM climate fields to drive a numerical ice dynamics model.

Structural evolution of surge-type glaciers: Application of structural glaciology methods in numerical ice dynamics models to interpret medial moraine pattern, stratification, foliation, fracture, and folding structures of Trapridge Glacier, Yukon.

Luke Copland, University of Ottawa

*Monitoring of glacier mass balance and dynamic*s, *Axel Heiberg Island, Nunavut:* Fieldwork and remote sensing studies, White and Good Friday Glaciers (with L. Thomson).

Iceberg production and drift in Canadian waters: Ship-based studies (CCGS Amundsen) on southeast Ellesmere Island, Nunavut.

Glacier and ice shelf changes on northern Ellesmere Island.

Dynamics of surge vs. non-surge glaciers in the St. Elias Mountains, Yukon (with C. Dow).

Connections between changes in shipping and sea ice conditions in the Canadian Arctic.

Christine Dow, University of Waterloo

Stability of Nansen Ice Shelf, Terra Nova Bay, Antarctica: Assess the impact of tides on grounding line stability; remote-sending and ground-based radar analysis of basal channels and transverse surface fractures that contributed to a large calving event in April 2016.
Modelling of the Aurora Subglacial Basin, East Antarctica: Ice dynamics and hydrological modelling to examine the controls on stability of Totten Glacier and ice shelf.
Hydrological modelling of Recovery Glacier, East Antarctica: Hydrological modelling (using GlaDS model) to look at the controls on subglacial lake growth and drainage.
Greenland supercooling freeze-on: Modelling to examine rates of supercooling freeze-on in the subglacial hydrological systems across the Greenland ice sheet.
Modelling of firn aquifers on Helheim Glacier, Greenland: Hydrological modeling to investigate the impact of firn aquifers on subglacial drainage development.
Dynamics of surge- and non surge-type glaciers in the St Elias Mountains, Yukon Territory: Fieldwork on Lowell Glacier and Kaskawulsh Glaciers to establish the controls on surging and assess whether the surging dynamics are changing in a warming climate.

Gwenn Flowers, Simon Fraser University

Geologic controls on glacier surge dynamics in the St. Elias Mountains, Yukon: Investigating mechanistic links between bedrock properties and glacier surging.

Modelling bedrock erosion and sediment transport in subglacial fluvial systems: Adapting fluvial erosion models to the subglacial environment to examine subglacial fluvial incision.

Climate sensitivity and fate of Barnes Ice Cap, Baffin Island, Canada: Evaluate the sensitivity of Barnes Ice Cap and project its response to recent and future climate and internal dynamics.

Point-scale to regional-scale variability of winter balance: Estimate winter mass balance across multiple scales in the St. Elias Mountains, Yukon, Canada.

Englacial hydrology of ice-dammed lakes: Evaluate the role of the englacial drainage system in outburst floods from ice-marginal lakes using an array of hydrological and geophysical instruments and surveys, St. Elias Mountains, Yukon, Canada.

Hester Jiskoot, University of Lethbridge

The effects of Arctic sea fog on glacier melt: Pan-Arctic approach to infer fog characteristics from remote sensing and meteorological data.

Tributary-trunk interaction and glacier response to climate change in western Canada: Fieldwork in the Clemenceau-Chaba icefield region, Canadian Rockies.

Reconstruction of Arctic weather and ice conditions from historical sources: Extraction of sea ice and weather data for East Greenland from a 1710 Dutch whaling expedition logbook.

Shawn Marshall, University of Calgary

Shallow ice cores and modelling of firn processes: Study of firn meltwater percolation and retention processes on the upper Kaskawulsh Glacier, St. Elias Mountains, and at Dye 2, Greenland, through shallow (10-40 m) cores and snow/firn-pit TDR arrays.

Climate downscaling for modelling glacier mass balance: Collaboration with UQAM to embed mountain glaciers in the Canadian regional climate model and develop subgrid strategies for modelling surface energy and mass balance.

Glacier-climate processes in the Canadian Rockies: Longterm studies of mass and energy balance processes and glacier runoff from Haig Glacier, Alberta.

Brian Moorman, University of Calgary

Application of AUVs to monitor glacier surface melt and hydrological processes: Ongoing field studies on Bylot Island, Canadian Arctic.

Brian Menounos, University of Northern British Columbia

Recent and past cryospheric change in western Canada: Response of alpine glaciers in western Canada to climate forcing over the last 10,000 years, based on terrestrial and lake evidence.

Monitoring seasonal snow cover and albedo: Remote sensing studies of large-scale snow cover, albedo, and glacier equilibrium lines. (Together with J. Shea).

LiDAR-based geodetic mass balance monitoring in western Canada: Airborne laser altimetry to measure seasonal mass change of the basins' glaciers and quantify the spatial distribution of winter snow cover in the Columbia Basin.

Hakai Cryosphere Node: In partnership with the Tula Foundation, monitoring of changes in the cryosphere along the British Columbia Coast, based on remote sensing, LiDAR, and high-elevation meteorological stations near Homathko and Klinaklini Icefields.

Derek Mueller, Carleton University

Ice shelf break-up processes and ice shelf epifaunal lakes: Geophysical and remote-sensing studies on Ellesmere Island, Arctic Canada and Nansen Ice Shelf, Antarctica.

Ice-ocean interaction in the Arctic: Monitoring and modelling the drift and deterioration of icebergs and ice islands, using remote sensing, ship-based research in Baffin Bay and Labrador, and community-based work (Iqaluit and Qikiktarjuaq, Nunavut).

Sea-ice topography using UAVs and structure-from-motion photogrammetry:

Joe Shea, University of Northern British Columbia

High-altitude meteorology, hydrology, and UAV-based glacier monitoring, Langtang Valley, Nepal: Collaboration between ICIMOD, Utrecht University, and Kathmandu University

UAV-based glacier monitoring, *Khumbu Valley, Nepal:* Collaboration between ICIMOD, IRD (France), Utrecht University, and Tribuvhan University.

Mountain meteorology and UAV-based snowpack studies, Canadian Rockies: University of Saskatchewan studies at Fortress Mountain and Athabasca Glacier, Alberta.

Laura Thomson, Queen's University

Mass balance of White Glacier, Axel Heiberg Island, Nunavut: Maintenance of the White Glacier mass balance program, initiated in 1959. Remapping and geodetic mass balance estimates of White Glacier using aerial photography collected in 2014. Joint with L. Copland.

Glacier mass balance reanalysis: Collaboration with Michael Zemp (WGMS)

Ice dynamics and temperature structure on White Glacier: Examination of multi-decadal White Glacier velocity slowdown, englacial ice temperature changes (joint with G. Flowers) and firn structure.

4. Selected Publications, 2015-2019

Bach E., V. Radić, and C. Schoof, 2018. How sensitive are mountain glaciers to climate change? Insights from a block model. *Journal of Glaciology*, 64 (244), 247-258, doi:10.1017/jog.2018.15.

Bash, E.A.R., *B.* Moorman, and A. Gunther, 2018. Detecting short-term surface melt on an Arctic glacier using UAV surveys. Remote Sensing, 10 (10), 1-17.

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SECTION C: SEASONAL SNOW
Report compiled by Alexandre Langlois, Université de Sherbrooke

1. Université de Sherbrooke (prepared by Prof. Alex Langlois)

1.1. Arctic research activities

During the 2015-2018 period, the Groupe de Recherche Interdisciplinaire sur les Milieux Polaires (GRIMP) has created and led a cryosphere monitoring network focusing on remote sensing, cryospheric processes and climatology. The group now includes 18 graduate students and has published numerous peer-reviewed papers, most of which 21 were first-authored by students. GRIMP initiated research projects and partnerships, from alpine to arctic regions, focusing on winter extreme events (WEE). More specifically, GRIMP began a large project in the Kitikmeot region (Nunavut) working on snow, sea ice, hydrology and caribou habitat characterization. We are now looking to develop a large monitoring network of WEE in the cryosphere to monitor the impacts of WEE on four main themes (Ecology-TH1; Hydrology-TH2; Geohazards-TH3 and Climate-TH4).
The long-term objective of our program to improve the monitoring of WEE in the cryosphere, through the development of a monitoring network in order to better predict and assess the multilevel impacts of climate change. The program focuses on two main approaches: remote sensing (AP1) and modeling (AP2). We refer to existing 'science gaps' that need to be addressed in order to properly monitor WEE using AP1 and AP2 at various scales. To fill these gaps, the following short-term objectives were pursued during the 2015-2018 reporting period: Theme-1: a) investigate linkages between snow conditions monitored from AP1 and simulated from AP2 with caribou presence/absence; b) investigate linkages between WEE occurrence and caribou presence/absence; c) use knowledge gained in a) and b) and integrate the information into the MaxEnt ecological model to predict presence/absence of caribou and project species distribution at the 2100 horizon using a climate model; and d) assess the impact of changing snow and sea ice conditions on caribou mobility. Theme-2: a) investigate the geochemical characteristics of winter snow cover and spring snowmelt; b) use observed geochemical values to determine snowmelt contributions to spring flow of major river systems; c) use model outputs from AP2 to predict the impact of future changes in snow cover to freshwater export into the marine system. Theme-3: a) use Unmanned Aerial Vehicles (UAVs), structure-from-motion (SfM) products and radar data to derive the presence of ice crusts; b) use AP2 outputs to develop an operational simulation platform producing spatialized snow melt and runoff for percolation studies; c) simulate SWE, melt and runoff at 1-km spatial resolution, validated using UAV snow maps from 4c) in order to improve flood forecasting at the watershed scale. Theme-4: a) use AP1 data to couple passive and active microwave data to retrieve snow state variables (large scale); b) improve existing remote sensing algorithms capable of monitoring WEE and evaluate spatial and temporal trends across the Arctic (large scale), c) develop a methodology to retrieve high-resolution snow and ice depth using UAVs (small scale); d) develop a freeze-thaw algorithm for active layer assessment using L-band passive microwaves; e) use model output from AP2 to evaluate future snow/soil conditions and albedo feedback at the 2100 horizon. The long-term objectives (15-20 years) will aim to provide a deeper understanding of the cumulative effects of WEE on the cryosphere using improved satellite imagery, modeling capabilities and monitoring instruments to widen the breadth of the program. The map below highlights our sampling locations near Cambridge Bay, Nunavut for the 2015-2018 reporting period:

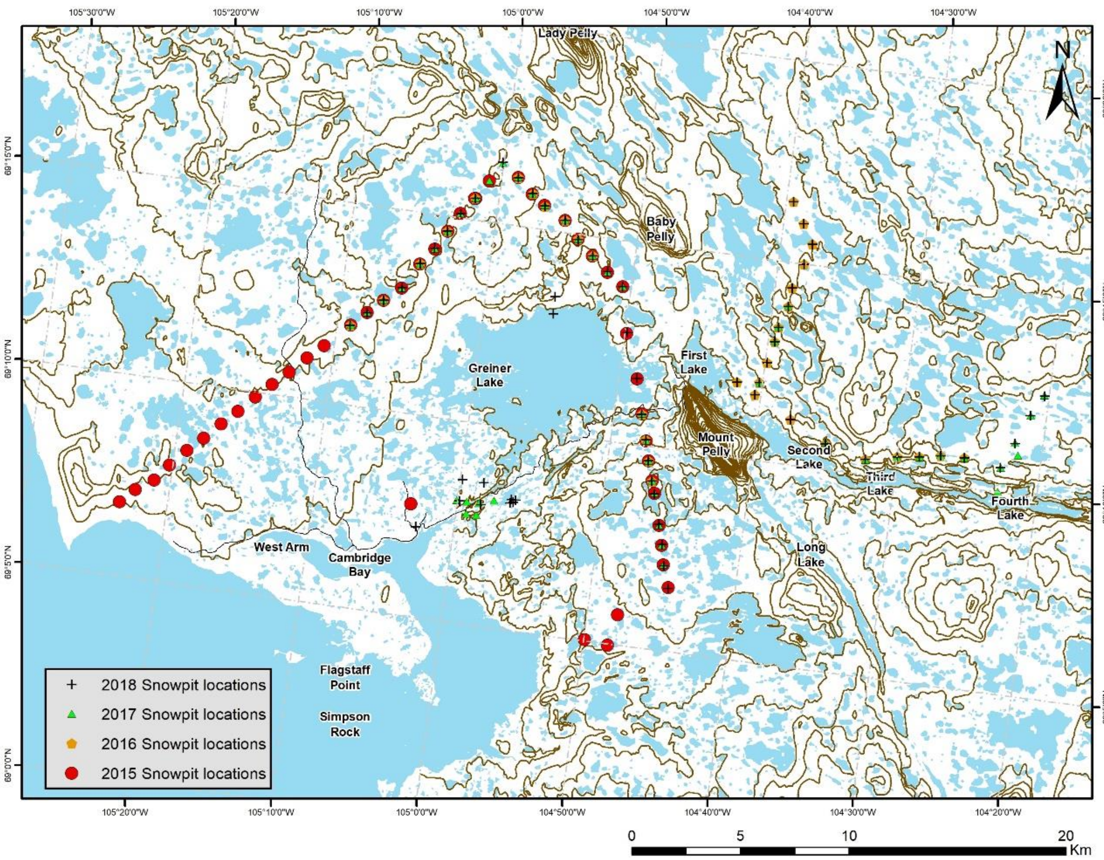

Figure: Snow study site locations between 2015 and 2018 in Greiner Watershed, Nunavut.

The research program provided continuity to initial work from the CoReH20 mission (Derksen et al., 2010) to bring attention to uncertainties in climate scenarios while improving the retrieval accuracy of surface state variables under WEE. Theme-1 work highlighted that snow density is a significant driver for caribou foraging conditions [Ouellet et al., 2017] and that winter storms and rain-on-snow events (ROS) can densify snow to a critical point for survival [Dolant et al., 2016; 2017; 2018; Langlois et al., 2017]. The Theme-2 work has shown that global remote sensing snow water equivalent (SWE) products are biased in wet snow conditions [Larue et al., 2017] however, snow models and radiative transfer models can improve the accuracy of retrievals when properly parameterized for soil, vegetation, ice layer presence and snow microstructure [Montpetit et al., 2018]. In Theme-3, we showed that current models poorly simulate water percolation within the snow with implications in ice layer development. Recent work on the implementation of the SNOWPACK in the Arctic model in Canada by our group showed that the sensitivity of the model to vapor flux contributing to kinetic growth metamorphism. It was also showed that the bias observed in snow grain size simulations depends on climate, suggesting regional patterns of the bias. Lastly, work in Theme-4 highlighted problems in precipitation phase parameterization from climate models that are enhanced with the increased occurrence of ROS. To date, there is no knowledge on what future snow conditions will be in alpine or arctic regions, and the use of state-of-the-art climate models coupled with snow remote sensing observations will help the understanding of the various processes governing spatial and temporal changes in snow, sea ice and permafrost conditions under WEE. We also identified potential biases in freeze-thaw retrievals using passive microwaves [Marchand et al., 2018] that can be linked to sub-pixel variability in freeze-thaw areas [Prince et al, 2018].

1.2. Avalanche research

Our group's avalanche program runs from the Chic Chocs in Québec, Glacier National Park in British-Columbia and Davos in Switzerland. Avalanches have been responsible for over 700 fatalities since the early 1780s in Canada alone. The majority of accidents occurred while people were engaged in recreational activities, while other accidents also occurred while traveling or working on transportation corridors. While the majority of the accidents occurred during recreational activities such as skiing and snowmobiling, it is not surprising to notice that almost 75 % of the fatalities are located in the British Columbia and Alberta where commercial mechanized backcountry recreation operations, such as helicopter and snowcat skiing, are mostly located. On these operations, mitigation operations are in place and include the use of guides that are responsible for the avalanche forecast however, the threat is not expected to be eliminated or even reduced until legislation and standards are in place.

Our program focuses on improving daily forecasts from a snow physical model (called SNOWPACK) that can in return be used by Parks Canada. The model can simulate snow conditions virtually everywhere, in near-real time, but an adaptation is needed to the Canadian climate conditions since the model was developed and adapted in Switzerland. The model can provide information where forecast are non-existent, but where tourism increases. In many areas where forecast are not available, an increase in tourist activity (which is expected to increase over the next 20 years) will increase the risk of an accident. Furthermore, in an era of climate change and increased accessibility to natural resources , the avalanche risk needs to be addressed, especially in northern regions where no mitigation procedures exist. With increased economic and recreational activities, the number of transportation corridors threatened by avalanches has also, and is expected to continue to, increase due to access roads being built for new mining, forestry and hydroelectric power generation operations.

The main objectives of the program are to:

- Adapt the SNOWPACK model to the reality of the various parks in Canada;
- Validate simulated snow physical properties and assess their impact on stability

Fieldwork was conducted every winter season of 2015-2018 in Glacier National Park, Jasper National Park and Réserve Faunique des Chic Chocs. Most of the work consisted in collected snow physical properties of interests in order to validate the model's performance in simulating stability. Madore et al. [2018] highlighted the fact that SNOWPACK overestimates snow grain size and that the bias is governed by the metamorphism equation in place (i.e. equilibrium metamorphism will lead to a different bias than kinetic growth metamorphism). We also showed that the model is sensitive to precipitation rate provided in input where the greater the precipitation rate, the greater the bias in simulated snow depths [Côté et al., 2018]. An automated platform of improved simulations was designed so that we now have near-real time simulations at our reference sites (i.e. Mt Fidelity in Glacier National Park, and Chic-Chocs). Each day at 6h00 E.S.T., simulations are updated, and an image highlighting main snow variables is produced and emailed to our partners. This is quite relevant since the information comes to them prior to their morning briefings. Here is an example:

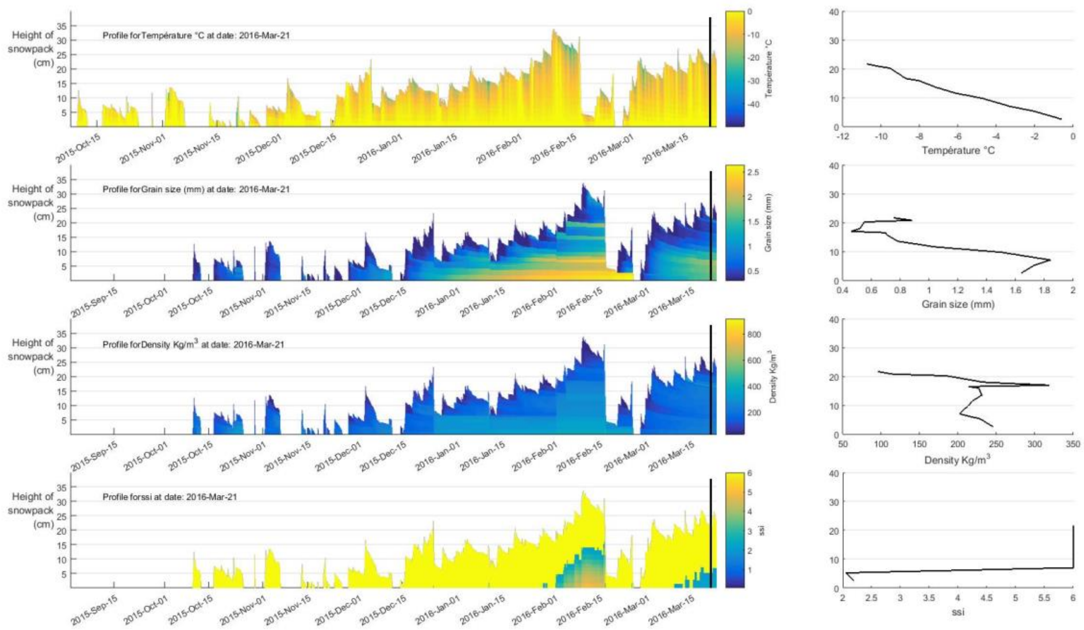

Figure: SNOWPACK simulation for Rogers Pass site, Glacer National Park, British-Columbia. The above figure includes all the necessary information to quantify snow stability. We are now in discussion with partners to identify sites of particular interest for which this can be produced. With the platform we now have, this can be done virtually anywhere, at any time. Obviously, other very significant work was conducted, in order to lead to this product. Our goal is now to continue this work and adding remote sensing data detecting rain events and adapt the SNOWPACK model for such conditions.

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2. Université Laval (prepared by prof. Sylvain Jutras)

2.1. Description of the Montmorency experimental forest

The NEIGE site is located at Forêt Montmorency, on the Canadian Shield and within the boreal biome. Dedicated to the study of snow, the NEIGE site was instrumented in 2014 under the coordination of Professor Jutras. It is now one of the only research facilities in Canada where many instruments configurations (> 30) are simultaneously measuring snowfall, snow depth and snow water equivalent, as well as ancillary weather conditions (> 30). It is also hosting three international reference instrument configurations for measuring snowfall (double fence intercomparison reference, double fence automatic reference and Bush shielded gauges). There are two operational weather stations operated by ECCC and the province of Quebec installed for intercomparison. The research site has involved many institutions (> 12) in research activities. To date, investments in cash, in-kind support, and equipment loans have exceeded $730,000, but less than 10% of this amount was available for HQP-oriented research. Currently, the NEIGE site is the most heavily equipped snow measurement experimental station in Canada. In addition, its location is recognized as having among the highest snowfall accumulation in eastern Canada, with 619 mm of snowfall recorded on average every year. It has more than 150 bi-daily snow events measured per winter during which 75% are over 3 mm of total precipitation. SWE has been measured for over 40 years via manual snow survey sites located in forest stands of various density within different watersheds located in the vicinity of the NEIGE site. More recently, many additional SWE sampling stations were added, as well as two isotopic attenuation automatic SWE sensors (CS725) installed close to these snow survey sites, for intercomparison purposes.

Figure: NEIGE site at the Montmorency experimental forest.

2.2. Training and outreach

Forêt Montmorency has a "teaching and research forest" status and it has been under the responsibility of Université Laval since 1965. This status enables long-term scientific projects through collaborative agreements. In addition, the team of professionals from the Forêt Montmorency works closely with the researchers to ensure a tight linkage between research and forest management. Forest ecosystems are described with a much higher level of precision and intensity than in typical boreal forests. This includes two full airborne high-density LiDAR coverage (> 412 km^2; 2011 and 2016), thousands of permanent and temporary forests stand sampling plots, highly detailed successive eco-forestry inventories and numerous aerial-photography archives. All this information is already available, which is enabling countless opportunities for sampling and surveying over the coniferous forest watersheds in the vicinity of the NEIGE site. This accessible knowledge will be central to the completion of the objectives linked to up-scaling snow measurement to the landscape level. Those tools will be of utmost importance for decision-making processes in water and resource management. Finally, the Forêt Montmorency has infrastructure for accommodations (> 100 rooms), meals (cafeteria open year-round), teaching (1 auditorium and 5 classrooms) and laboratories that can be adapted according to needs. The facility is accessible year-round and is only 80 km north of Quebec City. There is no other site located in the heart of Quebec's boreal forest that is easily accessible and welcoming, adapted to the needs of scientific research and HQP training in hydrometeorology. In Canada, there are currently < 15 solid precipitation intercomparison sites (Nitu et al. 2012) in operation. This network unites many scientific collaborators and research sites, developed in parallel with the WMO Solid Precipitation Inter-Comparison Experiment (SPICE). The NEIGE site is the only one located in the boreal biome of eastern Canada, which illustrates its uniqueness and relevance. Research collaborations are being established between the NEIGE site and other Canadian research and monitoring supersites, including Fortress Mountain (Alberta), Marmot Creek (Alberta), Wolf Creek (Yukon), CARE (Ontario), Bratt's Lake (Saskatchewan) and Caribou Creek (Saskatchewan).

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3. Wilfrid Laurier University (prepared by prof. Phil Marsh)

3.1. Arctic Hydrology at the northern treeline

Arctic Canada is warming at a rate up to three times the rate of the global average, with dramatic, yet poorly understood, effects on the hydrology of Arctic Canada. Our understanding continues to be limited by the lack of high quality hydrologic data across Arctic Canada, and significant limitations in both our understanding of Arctic hydrological processes and our ability to model changes to the hydrological system. As one of many examples, Shi et al. (2015) showed that air temperatures are warming during the spring melt period and as a result spring snowmelt is beginning earlier than in earlier decades. However, Shi et al. (2015) also showed that snowmelt driven streamflow is not occurring earlier in time. Such a change is unexpected and might be related to ongoing changes in other aspects of the Arctic environment. For example the active layer depth is increasing, shrub cover across the tundra is also increasing, and snowfall is decreasing. Understanding the interactions of these is difficult and highlights the need for hydrological research that considers the interactions between all key components of the hydrological system. To consider these hydrological changes, and improve our understanding and predictive ability, we have developed an integrated hydrological observatory with instrumented research watersheds in the vicinity of Inuvik, NWT. Havikpak Creek is a forested watershed located near Inuvik, while Trail Valley Creek is 50 km to the north. Trail Valley is primarily tundra with shrub patches and a few treed patches. Both are underlain by continuous permafrost. Over the last few years we have modernized the instrumentation at both sites with eddy covariance systems over forest, tundra, and lakes; a network of weather stations and shielded precipitation gauges and an upward looking weather radar; and cosmic ray sensors to continuously measure snow water equivalent throughout the winter and spring melt. A large solar/wind/generator power system allows these to be operated year-round. In addition, we are gauging streams from 58 km2 to 1 km2. These stream gauges are part of a larger network of 5 stream gauges operated by Environment and Climate Change Canada that stretch along a north-south transect from 100 km south of the treeline to tundra 100 km north at the Beaufort Sea Coast. Extensive remote sensing activities have been included in our research program, including Unmanned Aerial Systems to airborne radar for snow measurements, and collaborative studies with the NASA Arctic Boreal Vulnerability Experiment (ABoVE), and other international groups. Major field experiments include the 2018-19 TVCSnow experiment conducted with Environment and Climate Change Canada to study the ability of airborne radar to measure snow water equivalent, to a 2017 to 2018 Snowmelt Runoff Experiment. In addition we are using models such as the Cold Regions Hydrological Model and the CryoGrid permafrost model to help test our understanding of hydrological processes and to consider past and future changes.

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4. Environment and Climate Change Canada (ECCC) (prepared by Dr. Josh King)

Snow research activities of the Climate Processes Section (CPS) at Environment and Climate Change Canada (ECCC) between 2015 and 2019 can be categorized in three core areas: evaluation of trends in terrestrial snow mass, development of novel observation technologies, and snow on sea ice. Leveraging expertise within CPS, an integrated approach of field-based study, remote sensing, and model evaluation has been used to address questions regarding snow and climate, as well as develop new snow products to service operational mandates.

4.1. Trends in snow cover extent and mass

Robust trends in Arctic snow cover with quantitative estimates of uncertainty are required to support climate, hydrology, and ecosystem applications at ECCC. As a result, CPS has devoted significant time to the evaluation of existing products and development of new representations of snow extent and water equivalent in North America. As part of this work, a comparison of satellite-based and reanalysis-derived products demonstrated the large spread amongst estimates of snow mass in the Northern Hemisphere over the period of 1981-2010 (Mudryk et. al., 2015). Uncertainties of the input datasets were addressed and the value of ensemble estimates from multiple sources was identified. Sensitivity in snow cover extent trends in the CMIP5-generation of climate models was also evaluated, again highlighting the importance of an ensemble-based approach due to the large influence of natural variability and anomalous surface temperature–snow cover relationships (Mudryk et. al., 2017). ECCC research activities also identified improved representation of vegetation as a priority for accurate representation of snow in models. Winter albedo was found to be impacted in the CMIP5-generation of models where vegetation distributions are poorly represented, leading to uncertainties in the simulated snow-albedo feedback strength (Wang et. al., 2016). Where vegetation distributions are known is possible to apply a correction to account for intercepted snow and subsequent underestimation of the winter albedo (Bartlett and Verseghy, 2015).

Recent ECCC studies at sub-basin scales (10 km) have shown that where real-time snow depth estimates are ingested, operational products preform poorly with existing measurement infrastructure (Brown et. al., 2018a). Ongoing ECCC work hopes to provide quality controlled measurements of snow depth, snow density and snow water equivalent across Canada essential for validation in future studies (Brown et al., 2018b). Combined, the ECCC CPS analysis of terrestrial snow extent and SWE products suggests that (1) ensemble or blended datasets are of value for skill analysis and trend detection, (2) quality controlled inputs are critical for validation efforts, and (3) there is a strong need for near-real time inputs across North America.

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4.2. Novel approaches to observation of terrestrial snow mass

To address the observational gap of seasonal snow mass, ECCC, the Canadian Space Agency (CSA), industrial partners at Airbus Defence and Space, and international scientific collaborators have been working towards the development of a dual frequency radar (Ku-band: 13.5 and 17.2 GHz) mission concept to provide moderate resolution (<1 km) terrestrial snow water equivalent (SWE) across the Northern Hemisphere. Following technical trade-off studies, a concept capable of providing dual-polarization (VV/VH), moderate resolution (250 m), wide swath (~500 km), radar measurements was identified. In addition to a wide swath mode, a higher spatial resolution mode was identified to provide measurements at <50 m spatial resolution over critical watersheds in alpine environments, which are characterized by complex topography and therefore require finer sampling. Ku-band radar is a viable approach for a terrestrial snow mission because these measurements are sensitive to SWE through the volume scattering properties of dry snow and the wet/dry state of snow cover. Measurements at two different Ku-band frequencies have never been made from space before, and will mitigate sensitivity to snow microstructure, one of the main uncertainties in the retrieval of SWE from radar measurements (King et. al., 2018).

The SWE concept missions goal is to provide global coverage with a short revisit time (2-5 days) and latency (~12 hours) to meet requirements for operational applications, while providing a considerable increase in spatial resolution compared to existing and historical sensors with similar coverage and. The impact of sensor configuration on a potential mission and the operational products it would service was evaluated as part of an Observing System Simulation Experiment (OSSE; Garnaud, C., et. al. 2019). Parameters including spatial resolution and revisit frequency were evaluated using synthetic fields of SWE as input to the Canadian Land Data Assimilation System (CaLDAS). Increasing resolution, revisit frequency, as well as accuracy in the simulated products, reduced spatial error in CaLDAS. Reductions in spatial random errors of CaLDAS were possible with improved resolution and accuracy of the simulated SWE inputs. The findings of this study directly support the rational and requirements for a Canadian snow mass satellite mission.

Recently, ECCC CPS led a field campaign near Inuvik, NWT, Canada in support of the proposed satellite mission during the winter of 2018-2019. Field deployments were completed in November 2018, January 2019, and March 2019 to characterize the seasonal evolution of tundra snow within the Trail Valley Creek research basin. Airborne radar measurements were completed with a 13.5 GHz interferometric synthetic aperture radar (InSAR) developed by the University of Massachusetts during the same periods. Previous investigations of dual-frequency radar retrievals of SWE by lead ECCC researchers suggested that snow microstructure and background interactions were strong contributors to the observed signal (King et. al., 2015, 2018). However, if constrained, the influence of these uncertainties can be minimized to produce meaningful retrievals of SWE (Zhu et. al., 2018). As a result, the field experiment placed emphasis on spatiotemporal characterization of snow microstructure and soil properties across a variety of tundra land covers. Soil properties were characterized at 6 stations distributed throughout the basin where sensors buried 5 cm below the surface continuously measured soil temperature, volumetric water content, and permittivity. Spatial variations in snow microstructure were evaluated using 1310 nm laser reflectometry and measurements of the Snow Micro Penetrometer. Ongoing work will evaluate these measurements using a forward electromagnetic model to decompose the desired SWE signal from other influences.

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4.3. Snow on Sea Ice

In addition to terrestrial studies, ECCC has devoted resources to improving understanding of snow processes on sea ice. As an input to both climate studies (Howell et. al., 2016, Swart et. al., 2015) and operational prediction systems (Lemieux et. al., 2016), ECCC has focused on characterization at local to pan-Arctic scales through field work, airborne remote sensing, and model-based study. Initial work began in 2014 with a collaborative ECCC-NASA field campaign to evaluate radar-based snow depth retrievals as part of the NASA's Operation IceBridge (OIB). A 50 km snow depth transect was completed by ECCC CPS near Eureka, Nunavut, Canada within the swath of OIB's airborne snow radar. A direct comparison of the OIB estimates and ECCC in situ measurements of snow depth identified uncertainties related to roughness of the ice surface and the distances over which the radar returns were integrated (King et. al. 2015). This prompted further study of radar-based retrieval methods for snow on sea ice and documentation of their associated uncertainties (Kwok, et. al., 2017). A follow-on field study lead by ECCC in 2016 focused on small scale variability in snow and ice properties, again within OIB`s radar swath near Eureka, Nunavut, Canada. Using measurements of the Snow Micro Penetrometer and ground-based lidar, ECCC CPS was able to create 3-D representations of snow on the sea ice for parametrization of forward models. Ongoing work will attempt to quantify retrieval uncertainties and provide quantities error metrics to OIB snow products.

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5. Blowing snow and hydrology (prepared by Prof. John Pomeroy, University of Saskatchewan)

Blowing snow redistribution results in heterogeneous snow covers that are ubiquitous in cold, windswept environments. Capturing this spatial and temporal variability is important for melt and runoff simulations. A scalar transport model was discretized using the finite volume method (FVM), using parameterizations from the Prairie Blowing Snow Model (PBSM). The FVM approach allows for applicability to areas with divergent wind flow and does not require any upwind assumptions. PBSM has been applied in hydrological response units and grids to prairie, arctic, glacier, and alpine terrain and shows a good capability to represent snow redistribution over complex terrain. The FVM discretization takes advantage of the variable resolution mesh in the Canadian Hydrological Model (CHM) to ensure efficient calculations over small and large spatial extents. Variable resolution unstructured meshes preserve surface heterogeneity but result in fewer computational elements versus high-resolution structured (raster) grids. Snowpack observations were used to evaluate CHM-modelled outputs in a sub-arctic basin. The variable resolution resulted in a 90% reduction in total computational elements versus a fixed-resolution mesh. This reduction resulted in an 80% reduction in wall clock time. Valley drifts were well captured, and the spatial heterogeneity of the basin more closely matched observations than the no-blowing snow simulations. The results demonstrate the key role of snow transport processes in creating pre-melt snowcover heterogeneity.

Physically based glacier hydrological modelling is possible using standard meteorological inputs and glacier inventory information if methods to distribute calculations for snowfall, rainfall, blowing snow transport, avalanching, solar and longwave radiation, sublimation, melt energy, firnification, glacier configuration and runoff generation are incorporated into hydrological models. This has been accomplished through development of the modular, flexible, object-oriented Cold Regions Hydrological Modelling Platform (CRHM) in that a distributed model structure suitable for glaciated mountains has been created by including existing cold regions hydrology modules that have been applied to mountains around the world, and creating new ones dealing with avalanches, icemelt energy budget, firnification and sub-glacier flow. The model has been tested extensively using Peyto Glacier's 50+ year archival mass balance and hydrometeorological data at the headwater of the Saskatchewan River Basin in the Canadian Rockies, and subsequently applied to the Athabasca Glacier in the headwaters of the Athabasca River, the Llewellyn Glacier at the headwaters of the Yukon River and Bologna Glacier at the headwaters of the South Nahanni River. Changes in glacier hydrology are due to both changing climate and to changing glacier configuration.

A transect comprising three intensively researched mountain headwater catchments stretching from the northern US to northern Canada provides the basis to downscale climate models outputs for mountain hydrology and insight for an assessment of water futures under changing climate and vegetation using a physically based hydrological model. Reynolds Mountain East, Idaho; Marmot Creek, Alberta and Wolf Creek, Yukon are high mountain catchments dominated by forests and alpine shrub and grass vegetation with long-term snow, hydrometric and meteorological observations and extensive ecohydrological process studies. The physically based, modular, flexible and object-oriented Cold Regions Hydrological Modelling Platform (CRHM) was used to create custom spatially distributed snow hydrological models for these three catchments. Model parameterisations were based on knowledge of hydrological processes, basin physiography, soils and vegetation with minimal or no calibration from streamflow measurements. The models were run over multidecadal periods using high-elevation meteorological observations to assess the recent ecohydrological functioning of these catchments. The results showed unique features in each catchment, from snowdrift-fed aspen pocket forests in Reynolds Mountain East, to deep late-lying snowdrifts at treeline larch forests in Marmot Creek, and snow-trapping shrub tundra overlying discontinuous permafrost in Wolf Creek. The meteorological observations were then perturbed using the changes in monthly temperature and precipitation predicted by the NARCCAP modelling outputs for the mid-21st C. In all catchments there is a dramatic decline in snow redistribution and sublimation by wind and of snow interception by and sublimation from evergreen canopies that is associated with warmer winters. Reduced sublimation loss only partially compensated for greater rainfall fractions of precipitation. Under climate change, snowmelt was earlier and slower and at the lowest elevations and latitudes produced less proportion of runoff from snowmelt. Vegetation change scenarios counteracted increasing streamflow yields from climate change partly due to increased snow retention by enhanced vegetation heights at high elevations and reduced vegetation canopy coverage at low elevations.

The rapidly warming Arctic is also experiencing increasing shrub cover and density, and permafrost thaw. Understanding, quantifying and predicting the impact of these environmental changes on the hydrological regime of Arctic basins represents a great challenge, particularly due to the sparse monitoring network, limited understanding of governing physical processes and their interaction, and the uncertainty in future climate projections. The past, present and future hydrology of Havikpak Creek, a small (16.4 km2) Arctic basin located near the treeline in the Northwest Territories, Canada was investigated. A hydrological model suitable for application in the Arctic was developed using the Cold Regions Hydrological Model Platform (CRHM), including all the key physical processes found in this environment: flow through snowpack, organic terrain and mineral soil, evapotranspiration, infiltration into frozen and unfrozen soils, blowing snow redistribution and sublimation, snowpack energy balance, evaporation/sublimation from canopy interception of rain/snow, ground freeze and thaw and streamflow routing. The basin was discretized using hydrological response units based on elevation, landcover and topographic controls. Most physical processes are represented in CRHM using physically based parameterizations, which allows minimizing calibration. A historical run from 1960 to 2016 was performed using hourly in-situ observations and transient changes in vegetation cover, which revealed the model's capability to represent daily streamflow (RSE = 0.53, Bias=-9%), snow accumulation and melt (Bias = 11 mm), and active layer thickness (Bias = 8 cm). Mean water balance for the last 30 years showed that snowfall has been the largest water input (58%), whereas the water losses have been dominated by evapotranspiration (47%), streamflow (39%) and sublimation (14%). Great variability was found between different landcovers for most mass fluxes, demonstrating the need to include detailed vegetation characterizations in the model. To quantify potential changes associated with future climate and vegetation projections, the model was forced with 13 years of dynamically downscaled climate using a high-resolution (4-km) numerical weather prediction model (WRF) with a pseudo global warming configuration based on the RCP8.5 emission scenario (business as usual), as well as under a series of future vegetation characteristics to assess the model's sensitivity to changes in vegetation. Climate projections show a substantial increase in mean air temperature (6.1 oC), annual precipitation (117 mm) and incoming longwave radiation (21 W/m2); conversely, virtually no change in windspeed, incoming shortwave radiation and relative humidity is projected. The hydrological regime under these conditions presents a significant intensification of spring runoff, with a doubling of spring streamflow, earlier spring runoff, later fall runoff and increasing peakflow (30%). These changes are explained by the larger snow accumulation (45%), the shorter snow cover season (1 month) and greater runoff ratio. Mean active layer thickness increases by 30 cm (33%), expanding the ground storage capacity. Due to wetter and warmer conditions mean annual evapotranspiration increases by 30 mm, whereas mean annual sublimation shows a small increase of 2.5 mm, which is the result of the compensation between increasing canopy interception sublimation and decreasing sublimation at the snowpack's surface. The overall changes in climate from 1960 to 2100 at Havikpak Creek are profound, almost 10 degC of warming and a substantial increase in precipitation. Whilst the basin has shown hydrological resiliency to historical climate change it is predicted to respond in a very sensitive manner to future climate, suggesting that its hydrological resiliency will be suppressed with sufficient climate change.

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6. Satellite and Ground-based Microwave Remote Sensing of Snow. University of Waterloo (compiled by prof. Richard Kelly)

Our research group focuses on the development of methods to estimate global snow water equivalent (SWE) and snow depth using passive and active microwave satellite instruments. Global snow cover extent is changing as determined by sensors that can effectively monitor the presence of snow cover. However, there is a much wider range of uncertainties of SWE and the record is still not clear. The reason for this is that while modeling approaches can potentially predict snow mass at coarse spatial resolution, a) they are unverified by the observation record and b) lose skill at higher latitudes and higher spatial resolutions where there is greater uncertainty in parameterizing their boundary states. The spaceborne passive microwave record extends to 1972 but it is really only useable from 1979 onwards with the Scanning Multichannel Microwave Radiometer. With the Special Sensor Microwave Imager, the Advanced Microwave Scanning Radiometer ('-EOS' from NASA and '-2' from JAXA) the record is now 40 years in length. However, these coarse spatial resolution instruments (typically >100 km2 in footprint size) passive microwave systems were never designed to estimate SWE and so their use constitutes an opportunity to the science community to "wring" as much information from them as possible to estimate SWE. This is one area of our research through working with JAXA to develop an improved estimation product that has enhanced and independent capability to estimate SWE and snow depth regionally and globally. As part of this work, the research has focused on applying the work by Kelly et al. (2003) on the algorithm approach. The work of Li and Kelly (2017), Li et al. (in press) has focused on the estimation and correction of forest transmissivity for passive microwave retrievals. And the work by Saberi et al. (2017) focused on the use and parameterization of models applied in tundra snow environments. A special issue of the IEEE JSTARS publication was edited by Kelly (with others: Heygster et al., 2017). The work with Sarhardi et al. (2014) explored the use of passive microwave estimates of SWE in time series analysis and demonstrated that there is some skill in time series forecasting models.

A second area of cryospheric research is in radar remote sensing of snow with ground based Ku and X-band scatterometer system. This radar measurement system was deployed for two consecutive winter seasons in the Hudson Bal Lowlands, Churchill, MB from October-April, 2009-10 and 2010-11, and in Maryhill, Ontario from 2013-14 and 2014-15, to observe the evolution of seasonal snow and its impact on radar measurements. The research supported the Cold Regions Hydrology High-resolution Observatory satellite mission proposal at the European Space Agency. Ku band backscatter demonstrated a strong snow volume scattering signal and analyses demonstrated that Ku-band sensitivity at VV polarization to SWE is strong in tundra environments in the HBL with a 0.82 dB cm-1 increase in backscatter (R2 of 0.62) (King et al., 2015). Studies in southern Ontario have confirmed this result for moderate depth snowpacks (0.5-1m) with a similar sensitivity (Thompson and Kelly, 2015) and combined results from studies in Colorado (SnowEx 2017), Trail Valley Creek (2017) and S. Ontario (2014-2017) have demonstrated further skill in the Ku-band radar approach (Thompson and Kelly, 2019). Overall, the science observation-based results are providing a strong impetus for our group to deepen our knowledge about the impact of forest cover, buried vegetation and organic soils on the Ku and X-band radar response of snow. As a result of this research effort we are in the process of acquiring an L-band and Ku-band airborne radar system, The CryoSAR, for a community of researchers across Canada to conduct cryospheric research discovery experiments from an airborne SAR imaging system.

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7. Snow Hydroclimatology. University of Northern British Columbia (compiled by Prof. Stephen Déry)

Background: British Columbia's (BC's) mountains are often called its 'water towers', as they receive disproportionately high amounts of precipitation (particularly in the form of snow) often through orographic enhancement (Immerzeel et al. 2010). The timing and rate of the snowpack's melt is thus a key control on spring and summer soil moisture and river flows, in turn affecting water availability and security for community, agricultural, industrial, and ecological requirements. The Intergovernmental Panel on Climate Change (IPCC 2013) anticipates increases in precipitation across BC in future decades, but there is substantial uncertainty over associated quantities, phase and timing. This is exacerbated by data-paucity in BC's remote, complex terrain such as in the Cariboo Mountains where observational densities meet only a few percent of the World Meteorological Organization's recommendations (Miles et al. 2003).

Recent progress: To improve monitoring in data sparse regions of BC, Dr. Déry established the Cariboo Alpine Mesonet (CAMnet; Hernández-Henríquez et al. 2018) in 2006. CAMnet is now a network of 15 weather stations in mountain and valley settings at elevations ranging from 744 m to 2105 m. Data from these weather stations have supported modeling studies of seasonal snowpack evolution (Younas et al. 2017), blowing snow fluxes (Déry et al. 2010), turbulent fluxes on a mountain glacier (Radić et al. 2017), and pro-glacial sediment transport dynamics (Leggat et al. 2015). These data have also been used to validate remote sensing products of snow (Tong et al. 2009a, b) and gridded meteorological datasets (Sharma and Déry 2016). More recently, CAMnet stations have provided hydrometeorological data to researchers investigating the long-term physical and biochemical effects of the Mount Polley mine tailings impoundment breach in August 2014 on Quesnel Lake (Petticrew et al. 2015).

Other ongoing research is elucidating the frequency, intensity and impacts of landfalling atmospheric rivers (ARs) on BC's Pacific Coast. ARs were first recognized in the mid-1990s as narrow but elongated meridional moisture plumes that transport abundant water vapor inducing extreme precipitation events. They usually stretch from tropical to temperate latitudes, such as from Hawaii towards the Pacific Coast of North America, where they are known as 'Pineapple Express' storms. In BC, interaction with coastal, mountainous terrain often results in further enhancement of precipitation. Given their importance, this effort is yielding a comprehensive climatology of AR landfalls in southeastern Alaska and BC to explore their contributions to annual precipitation and extreme hydrological events. On average, 35 ARs make landfall annually in coastal BC and southeastern Alaska with the highest frequency in fall (Sharma and Déry 2019). They also contribute up to 35% of total annual precipitation in BC and up to 90% of annual extreme snowfalls, especially at higher elevations.

Another major effort led by Dr. Déry has led to expertise in state-of-the-art modeling tools to simulate current and projected changes in snow hydrology across BC. To simulate hydrological processes, the Variable Infiltration Capacity (VIC) hydrological model (Liang et al. 1994, 1996) has been implemented across the Fraser River Basin (FRB) at 1/4° spatial resolution. The VIC simulations, driven by historical observed datasets, report declining mountain snowpacks, earlier melt onsets with advances in spring freshets, and reductions in summer flows from 1948 to 2006 (Kang et al. 2014, 2016; Islam and Déry 2017). The model has also been driven by statistically-downscaled global climate model (GCM) output from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012) to study projected hydrological changes in the FRB (Islam et al. 2017, 2019; Curry et al. 2019). Recently, an updated and re-engineered version of the VIC model coupled to glacier mass balance and dynamics modules (VIC-GL) was acquired and implemented on the Stikine River Basin at high spatial (1/16°) and temporal (3-hourly) resolution using parallel computing. This will yield an assessment of historical changes in the basin's regional hydrology with a focus on quantifying glacier and snow melt contributions to runoff generation.

Other efforts have explored Northern Hemisphere (NH) snowcover extent (SCE) trends given this is a sensitive indicator of climate change. Building on previous work, Hernández-Henríquez et al. (2015) found significant declines in SCE during spring and summer over North America and Eurasia for 1972-2014, revealing a polar amplification of negative trends in SCE. There was also elevation dependence of SCE over time as statistically significant negative trends occurred at most elevations. These significant negative trends exhibited at high latitudes and elevations provided evidence of polar amplification and elevation dependence of trends in snowcover in a warming climate, suggesting a leading role of the snow albedo feedback. Allchin and Déry (2017) expanded on this work to establish regional SCE trends and their monthly variations across the Northern Hemisphere, further revealing a strong latitudinal dependence on observed SCE changes from 1971 to 2014.

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8. Avalanche Studies: Simon Fraser University (compiled by Dr. Simon Horton)

The SFU Avalanche Research Program applies a multi-disciplinary approach to avalanche safety including hazard assessment, terrain management, user groups, etc. The hazard assessment research theme is most relevant to snow and avalanche science. The goal of this theme is to improve our ability to assess and communicate avalanche hazard information by capturing the assessment expertise of avalanche professionals and develop decision support tools. Central to research in this area is the Conceptual Model of Avalanche Hazard

(CMAH, Statham et al., 2018), which provides a tangible pathway for how to derive an avalanche hazard assessment from avalanche safety observations.

8.1 Seasonal avalanche hazard forecasting

While the effect of large-scale climate patterns (e.g., El Niño-Southern Oscillation) on winter temperature and precipitation in western Canada is relatively well understood, little is known regarding the link between climate and avalanche hazard. Using avalanche hazard assessments from Avalanche Canada and Parks Canada from the 2010 to 2017 winter seasons, the nature and variability of avalanche hazard was related to large-scale climate patterns (Shandro and Haegeli, 2018). Typical avalanche hazard situations were identified with the CMAH, and their seasonal prevalence was calculated. The relationship between the prevalence of these hazard situations were compared to climate variabilities. This study suggests a relationship between the climate patterns and avalanche hazard situations with a method that is more informative for avalanche risk management.

8.2 Linking avalanche danger ratings to avalanche problems

Daily avalanche bulletins are prepared by Avalanche Canada and Parks Canada to communicate avalanche hazard information to the public in western Canada. While the CMAH provides avalanche forecasters with a framework for assimilating observations and characterizing avalanche hazard in a structured way, it does not provide guidance on how to rate the conditions according to the North American avalanche danger scale, a ordinal five-levels scale, which is used to communicate the general character of the conditions to the public. Using avalanche bulletin databases of Avalanche Canada and Parks Canada (2010 to 2017), this research established a quantitative link between hazard assessments according to the CMAH and avalanche danger ratings using a variety of supervised machine learning techniques (Clark, 2019).

8.3 Exploring regional snowpack patterns with a coupled weather and snowpack model

The development of physical snowpack models has been an active research field in the past two decades, but they have had limited adoption by avalanche operations. At the 2016 International Snow Science Workshop, we began collaborating with international snowpack model users and helped prepare an status report with recommendations for improved collaboration (Morin et al., submitted). This work identifies one of the major barriers to adoption has been difficultly interpreting meaningful information from the vast amounts of data produced by these models. Since then we have begun a project with the objective of simplifying and visualizing the output of physical snowpack models. We developed methods to identify key snowpack features within a region and characterize their variability, providing a simplified representation of the snowpack (Horton et al., 2018). This information can be shared with avalanche forecasters in a way that could help them assess the hazard in remote or data sparse areas. As part of this project, infrastructure for producing large batches of snowpack simulations has been developed, laying the groundwork for upcoming research.

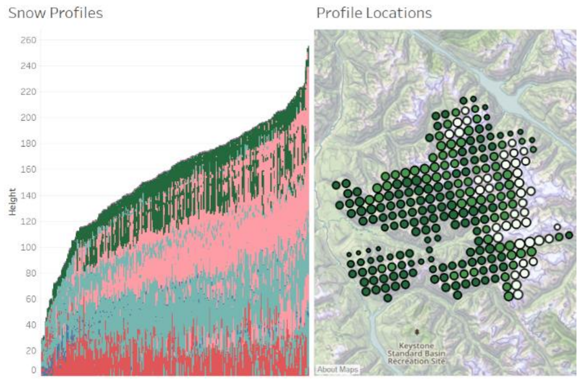

Figure: Example of a regional snowpack summary produced by viewing 300 simulated snow profiles side-by-side.

8.4 Integrating avalanche problems into snowpack models

We are examining the relationship between avalanche problems from identified in public avalanche bulletins with the output from weather and snowpack models. The goal is to develop a small number of pilot models that predict the existence and characteristics of avalanche problems based on modeled weather and snowpack observations.

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9. Snow-Climate Interactions, University of Waterloo, (compiled by Prof. Christopher Fletcher)

Significant progress has been made since 2015 in understanding and quantifying the physical processes governing the distribution and variability of snow, and their representation in earth system models. The Canadian Sea Ice and Snow Evolution (CanSISE) network was a federally-funded group of academic and government researchers, with a key deliverable to evaluate the representation of terrestrial snow in the second generation Canadian Earth System Model (CanESM2) for historical and future projections (Kushner et al. 2018).

In other work supported by CanSISE, a series of contributions have improved understanding of the physical processes controlling snow albedo feedback (SAF), which amplifies climate warming in cold regions through a reduction in surface albedo from melting snow and ice (Thackeray and Fletcher 2016). A particular focus was on the quantification of biases in simulated SAF among the most recent generation of IPCC-class ESMs from CMIP5, and causes of intermodel spread (Fletcher et al. 2015). The northern boreal forests have been identified as regions of particularly large uncertainty in simulations of SAF, because of the complexity in representing interactions between falling snow, the forest canopy, and the ground surface below. Our work has highlighted a large intermodel diversity in biases, and errors in the timing of the seasonal cycle, of simulated surface albedo in northern boreal forests (Thackeray et al. 2015).

More recent work has documented a novel "prescribed-albedo" methodology, implemented in the NCAR Community Earth System Model (CESM), which we have used to diagnose the impacts of surface albedo biases on surface climate in CMIP5 models (Thackeray et al. 2019). The findings highlight that correcting albedo biases in the seasonal cycle of albedo in CESM can improve the simulation of climatological spring near-surface air temperatures, and is connected to the simulation of remote atmospheric circulation anomalies over the Arctic. However, this methodology revealed compensating errors in CESM, which meant that overall climate biases are not always reduced by correcting surface albedo.

Continuing our focus on the northern boreal forests, work led by CanSISE-supported student Markus Todt and colleagues at Northumbria University, has quantified the importance of enhanced downwelling longwave radiation (LWE) from evergreen forest canopies. In Todt et al. (2018) we showed that the CESM land surface model is biased low in representing LWE because, like most other CMIP5-class land surface models, it uses a single-layer vegetation scheme, which causes a greatly overestimated diurnal cycle in canopy vegetation temperature. This work has led to the development of a new computationally-efficient physical parameterization to mimic the effects of a two-layer vegetation canopy, which damps the diurnal cycle of canopy vegetation temperature, and results in improved representation of LWE, and an approximately two-week delay in snowmelt (Todt et al. 2019).

Ongoing research funded by the Canadian Space Agency is focused on using CloudSat-CPR retrievals of snowfall rate to estimate snow accumulation over the Arctic. CloudSat data is being used to develop a quality flag for gridded Blended-4 SWE products (King and Fletcher, in preparation). The accuracy of CloudSat's 2C-SNOW-PROFILE product in detecting the occurrence of snow at locations across Canada has been quantified at 70-80 % (Kodamana and Fletcher, in preparation). At the Eureka station (high Arctic, 80oN), where instrumentation allowed a more in-depth comparison, accuracy was found to be even higher (>90 %) when surface snowfall rates are relatively heavier (>0.5 mm/hr), and accuracy is considerably lower (<50\%) when surface snowfall rates are light (<0.5 mm/hr). Reasons for these issues include higher incidence of virga under light snow conditions, combined with the effect of ground clutter making CloudSat retrievals largely unusable below 1,500 m altitude (Stephens et al. 2017).

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10. Studies on physical processes in Arctic snowpacks, University of Laval (compiled by Prof. Florent Domine)

Arctic snow studies since 2014 have come to the conclusion that it was not possible to simulate most physical properties of Arctic snowpacks using currently available detailed snow physics models such as Crocus and SNOWPACK. This was first demonstrated by (Domine et al., 2016b) and subsequently detailed in (Barrere et al., 2017). The main reason is that the vertical water vapor flux generated by the strong temperature gradient in Arctic snowpacks (>100 k m^{-1} for several months) generated a strong upward water vapor flux that produced mass loss in the lower depth hoar layer and mass gain in the upper wind slabs. Since models do not simulate this process, density profiles were not simulated adequately. In particular, models simulate dense lower layers and light upper layers, while the opposite is observed in the Arctic. Density is a key determinant of other snow physical properties in snow models (e.g. thermal conductivity), and therefore other physical properties are not simulated correctly by models either. Snow physics models that include water vapor transport are urgently needed to describe Arctic snow. This is even important for climate and meteorological models, as snow properties determine heat exchanges between the atmosphere and the ground through the snow, and therefore atmospheric temperatures, as illustrated in (Domine et al., 2019).

Further illustrating the peculiarities and variability of Arctic snowpacks, investigation in polar deserts of the very high Arctic revealed that depth hoar may not form in some Arctic snowpacks where soil moisture is low (such as in polar deserts) and where wind speeds are high (Domine et al., 2018a). This is because the lack of moisture allows fast ground cooling, preventing the persistence of a strong temperature gradient in the snowpack, while high wind speeds form dense wind slabs where depth hoar formation is hindered. Growing vegetation on polar deserts due to warming may therefore change soil moisture, snow properties and therefore the thermal regime of permafrost.

Other snow-vegetation interactions can also affect the ground thermal regime. Shrub growth on Arctic tundra is often thought of as a cause of ground warming because of enhanced snow depth and increased formation of low thermal conductivity depth hoar (Domine et al., 2016a). However we observed that the increased occurrence of warm spells in fall can lead to the preferential formation of dense hard conductive melt-freeze layers in shrubs, because they absorb radiation and favor melting. This process can contribute to ground cooling under shrubs (Barrere et al., 2018), so that further warming could actually cancel the soil warming effect of shrubs.

Finally, snow properties can strongly influence population dynamics of mammals. This was demonstrated for lemmings in the high Arctic, where winter population growth was inversely linked to the occurrence of warm spells in the fall (Domine et al., 2018b), which produce hard refrozen layers. Lemmings live in the sub-nival space and have easy access to food when basal layers are soft while harder layers impede their travels and access to food.

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SECTION D: PERMAFROST

Report compiled by A. Lewkowicz, University of Ottawa

President, Canadian Permafrost Association (2018-2019), Chair, Canadian National Committee for the International Permafrost Association (2017-2020)

Permafrost research in Canada 2015-2018

Permafrost research is being carried out across northern Canada by numerous individual researchers and groups. In recent years, there have been several faculty appointments relating to the study of permafrost, including Ryley Beddoe (Queen's), Philip Bonnaventure (Lethbridge), Pascale Roy-Leveillée (Laurentian), Suzanne Tank (Alberta) and Robert Way (Queen's), representing a renewal of the professoriate after the retirements of a number of prominent researchers. These appointments show the growing recognition of the importance of permafrost change to the infrastructure and ecosystems in the Canadian North and through the emission of greenhouse gases from thawing permafrost, to global climate change.

Table 1 is a list of government and university-based researchers from across Canada involved in the study of permafrost. The list is not comprehensive as it omits the many graduate students writing theses, and practitioners based in consulting companies (such as BGC, Tetratech and Canadrill) or governments (e.g. Transport Canada, Yukon Highways and Public Works, NWT Infrastructure) who undertake applied research. The study of permafrost bridges earth science and engineering, but also involves researchers in cognate fields, such as ecology, atmospheric sciences and in some cases, the social sciences. Therefore, Canadian researchers who have an interest in permafrost are more numerous than those listed. Furthermore, there are a considerable number of international researchers working regularly in Canada, especially in relation to EU-, NSF- and NASA-funded projects.

Table 1 demonstrates the uneven geographic coverage of permafrost research across the North. For example, there are relatively few researchers active in the northern parts of the provinces (except Nunavik) and there are still large spatial gaps in basic information such as ground temperatures in the central Arctic and at high elevations in the Rocky Mountains.

Table 1. Canadian university, college and government-based researchers involved in studies focused on permafrost, by study region (2015-2018)

Study region	Researcher name and institution
Labrador and Nunatsiavut	Trevor Bell (Memorial) Antoni Lewkowicz (Ottawa) Robert Way (Queen's) Yu Zhang (CCMEO)
Nunavik	Michel Allard (Laval) Daniel Fortier (Montreal) Richard Fortier (Laval) Warwick Vincent (Laval)
Nunavut	Stéphanie Coulombe (Polar Knowledge Canada) Caroline Duchesne (GSC) Mark Ednie (GSC) Daniel Fortier (Montreal) Scott Lamoureux (Queen's) Melissa Lafrenière (Queen's)

	Anne-Marie LeBlanc (GSC) Brian Moorman (Calgary) Greg Oldenborger (GSC) Wayne Pollard (McGill) Wendy Sladen (GSC) Sharon Smith (GSC) Warwick Vincent (Laval) Kathy Young (York)
Northern Ontario	Pascale Roy-Léveillée (Laurentian) Yu Zhang (CCMEO)
Northern Manitoba	Leeann Fishback (CNSC) Wendy Sladen (GSC)
Northern Alberta and Rockies	Philip Bonnaventure (Lethbridge) Antoni Lewkowicz (Ottawa)
Southern NWT	Fabrice Calmels (Yukon College) Laura Chasmer (Lethbridge) Antoni Lewkowicz (Ottawa) William Quinton (Laurier) Ashley Rudy (Laurier) Sharon Smith (GSC) Merritt Turetsky (Guelph) Steve Wolfe (GSC)
Northern NWT	Chris Burn (Carleton) Claude Duguay (Waterloo) Robert Fraser (CCMEO) Stephan Gruber (Carleton) Jocelyn Hayley (Calgary) Kumari Karunaratne (GNWT) Steve Kokelj (GNWT) Denis Lacelle (Ottawa) Philip Marsh (Laurier) Ashley Rudy (Laurier) Trevor Lantz (Victoria) Peter Morse (GSC) Rod Smith (GSC) Suzanne Tank (Alberta)
Northern British Columbia and Rockies	Alexandre Bevington (Government of BC) Martin Geertsema (Government of BC / UNBC) Antoni Lewkowicz (Ottawa)
Yukon	Jeff Bond (YGS) Philip Bonnaventure (Lethbridge) Chris Burn (Carleton) Fabrice Calmels (Yukon College) Guy Doré (Laval) Daniel Fortier (Montreal) Duane Froese (Alberta) Antoni Lewkowicz (Ottawa)

	Panya Lipovsky (YGS) Wayne Pollard (McGill) Bernhard Rabus (Simon Fraser) Louis-Phillipe Roy (Yukon College) Pascale Roy-Léveillée (Laurentian) Sharon Smith (GSC)

Most of the university-based researchers listed in Table 1 hold individual NSERC Discovery grants to support their research programs. Government-based researchers are financed by their internal programs. In addition, there have been several large collaborative grants which supported permafrost research during 2015-2018:

- The Arctic Development and Adaptation to Permafrost in Transition (ADAPT) project was funded by an NSERC Discovery Frontiers grant (2011-2016). It brought together 15 laboratories across Canada and many collaborators to develop an integrated Earth systems science framework on diverse aspects related to thawing permafrost conditions in the Canadian Arctic. Led by Warwick Vincent (Laval), it focused on how changing permafrost and snowfall affect tundra landscapes, water and wildlife, and the implications for northern communities and industries who depend on these resources (Vincent et al. 2013, 2017).

- ArcticNet, led by Louis Fortier (Laval) was funded until 2018 by the Network of Centres of Excellence program and included a significant component of permafrost research. Permafrost researchers played important roles in three of ArcticNet's Integrated Regional Impact Studies (IRIS) which were carried out as part of the overall program and published between 2012 and 2018: Allard and Lemay (2012), Stern and Gaden (2015), and Bell and Brown (2018). ArcticNet has applied for a renewal of its mandate but no announcement has been made to date.

- In 2018, Stephan Gruber (Carleton University) led the development of a successful Letter of Intent for PermafrostNet, an NSERC Research Partnership Network focused on permafrost. The proposed network is focused on permafrost thaw and will involve numerous universities across Canada and a wide range of partners in federal and territorial governments, as well as communities. The results of the full application will be known in summer 2019.

Research highlights 2015-2018

A common theme for permafrost research across Canada is the effect of environmental change, including climate warming, on permafrost conditions. Topics range from evaluating long-term climate change during the Quaternary from the isotopic composition of ground ice (e.g. Porter et al. 2016), to the impact of future climate change on northern infrastructure (e.g. Doré et al. 2016), to the effect of permafrost thaw on mercury release (e.g. St Pierre et al. 2018). Such works require an understanding of long-term change acquired variously through field investigations (including monitoring), laboratory analyses, remote sensing and modelling, or combinations of these approaches.

Perhaps the most impressive scientific advance in the 2015-2018 period concerns the causes and rapidity of development of thermokarst (landforms and processes associated with the melting of ground ice). Olefeldt et al. (2016) recognized and mapped regional coverage of three different thermokarst landscapes for the entire northern boreal and tundra circumpolar region: wetland thermokarst, lake thermokarst and hillslope thermokarst. There are extensive areas of Canada falling into these landscape types, especially in the northwest. Publications on the development of retrogressive thaw slumps across this region (Kokelj et al. 2017), and more specifically on the Peel Plateau (e.g. Lacelle et al. 2015) and Banks Island (Segal et al. 2016, Rudy et al. 2017) show the major changes underway in these landscapes. Studies of active-layer detachments (Rudy et al. 2016) on Melville Island and the development of melt ponds over degrading ice wedges in relatively flat area of Banks Island (Fraser et al. 2018) demonstrate other types of landscape change that can be detected by remote sensing. Together they reveal an unexpected vulnerability of ice-rich cold permafrost to changes in summer climate. Until recently, such landscapes were thought to be excellent indicators of climate change, as shown through progressive warming of the permafrost (AMAP 2017), but to be buffered by their cold ground temperatures from other impacts. This research shows that this is not the case in regions where bodies of ice-rich permafrost, themselves linked to Quaternary history (Kojkelj et al. 2017), are present close to the ground surface. In contrast, examination of a transect of eastern Canada from 1999-2016 using remote sensing found that few thaw slumps developed and that lake enlargement was a much more important change (Nitze et al., 2018).

Farther south, one of the major disturbances to the boreal forest is forest fire (Nitze et al. 2018). This too has impacts on permafrost, resulting in a warmer and deeper active layer and spatial expansion of taliks (Gibson et al. 2018). The expansion of thermokarst bogs, however, is not dependent on fire as ongoing warming is causing progressive loss, as shown in the long-standing hydrological and ecological research being undertaken in Scotty Creek, NWT (Quinton et al. 2018). The insights gained in that basin are showing the irreversible landscape change that accompanies ice-rich permafrost loss in zones of discontinuous permafrost.

There are numerous examples of excellent applied studies on permafrost being undertaken by Canadian researchers. These are often the most important research projects at the community level because they respond directly to the needs of northern residents. Examples include research to find suitable land for the expansion of housing in Salluit in northern Québec (Vincent et al. 2017), a study to examine the impact of permafrost degradation on food security at Jean Marie River, NWT (Calmels et al. 2015) and climate change adaptation projects for Yukon communities (Benkert et al. 2015a, 2015b, 2015c, 2016).

The largest permafrost engineering project undertaken in Canada during the reporting period was construction of the 138 km long Inuvik to Tuktoyaktuk Highway (ITH) from 2014-2017. The highway traverses permafrost that is ice-rich in many places on its way to the Arctic coast. The access granted by this new infrastructure is being used to monitor transects of undisturbed sites and to examine highway performance. For example, results from the University of Manitoba research site at km 82+375 of the ITH include the effect of geotextiles on the deformation behaviour of high fill embankments built during winter (De Guzman, 2015; De Guzman *et al.*, 2016; 2017), and the thermal behaviour of a culvert through the highway embankment (Kaluzny *et al.*, 2018).

Additional details on permafrost research can be found in the Canada country reports for 2015 and 2017 prepared for the International Permafrost Association at https://ipa.arcticportal.org/publications/ipa-country-reports.

Meetings 2015-2018

The 7th Canadian Permafrost Conference was held jointly with the 68th Canadian Geotechnical Conference at GEOQuébec in 2015 and was co-sponsored by the Canadian National Committee for the International Permafrost Association (CNC-IPA) and the Canadian Geotechnical Society. CanCoP7 was dedicated to the memory of J. Ross Mackay and also featured the inaugural Mackay lecture. An entire day was devoted to the Mackay Symposium which featured presentations by international colleagues as well as Canadians.

Numerous Canadian researchers also attended the major international conferences on permafrost during 2015-2018: the Eleventh International Conference on Permafrost in Potsdam, Germany in June 2016 and the Fifth European Conference on Permafrost in Chamonix, France, in June 2018. The IPA moved to holding a regional conference every year during this period and there was also good Canadian attendance at the Second Asian Conference on Permafrost in Sapporo, Japan, in July 2017.

Organisation of permafrost research in Canada

As mentioned above, permafrost research in Canada (and in general) is undertaken by researchers and professionals in a wide range of disciplines. These include geography, geology, hydrology, climate science, soil science, remote sensing, geotechnical and transportation engineering. As a result, the permafrost community in Canada has been dispersed across numerous institutions and associations. The latter include the Canadian Association of Geographers, the Canadian Geophysical Union, the Geological Association of Canada, the Canadian Geomorphological Research Group, and the Cold Regions Division of the Canadian Geotechnical Society.

Until 2018, the only group that represented the entire gamut of permafrost research was the Canadian National Committee for the International Permafrost Association (CNC-IPA). The CNC-IPA was formed in 1985, soon after the formation of the IPA itself, and initially was under the auspices of the National Research Council. More recently, members of CNC-IPA have been appointed by the Geological Survey of Canada which also houses the Secretariat, while the Chair is chosen by the members. The current chair (2017-2020) is Antoni Lewkowicz (University of Ottawa). CNC-IPA is responsible for sending Canada's dues to the IPA and holds Canada's seat on the IPA Council.

IPA is a member of IUGS but it has links to IUGG through the IPA-IACS joint Glaciers and Permafrost Hazards in High Mountain Slopes Working Group. Canada has been very active in the IPA, and two Canadians have been president: Hugh French (1998-2003) and Antoni Lewkowicz (2012-2016). Chris Burn (Carleton University) was made Senior Vice-President in 2018 and so will automatically become president for 2020-2024.

When the members of CNC-IPA were appointed in 2017, they decided to set up a Steering Committee to explore the need for a Canadian Permafrost Association (CPA). After working for 5 months to develop and approve the CPA's mission, constitution and by-laws, the 19-person Steering Committee nominated the first Board of the CPA and subsequently disbanded. The CPA formally came into existence as a non-profit organisation in March 2018 with a board composed of a President (Antoni Lewkowicz), Secretary (Peter Morse, GSC), Treasurer (Lukas Arenson, BGC Engineering), Communications Director (Ashley Rudy), Early Career Member Representative (Carolyn Gibson) and three members-at-large: (Wayne Pollard (McGill), Isabelle de Grandpré (GNWT) and Richard Trimble (Tetratech). By the end of 2018, the CPA had almost 100 paid-up members, including 9 lifetime members and 7 corporate or institutional members.

The formation of the CPA is regarded as one of the most important recent steps for permafrost research in Canada given its mission *to bring communities, researchers and* *practitioners together to advance understanding of permafrost environments*. For the first time, a forum is available for exchanging needs and knowledge centered exclusively on permafrost. The CPA held a very successful first Annual Meeting at Yukon College in Whitehorse in October 2018 which included a one-day field course on the use of electrical resistivity tomography for permafrost investigations. The Association is one of the sponsors of the 2019 International Conference on Cold Regions Engineering / 8th Canadian Permafrost Conference which will be held in Québec City in August 2019. In its first use of funds to support the Canadian permafrost community, the CPA announced it would pay the registration fees for up to 10 early career researchers to attend this conference. It also offered its members reduced registration fees for a short course on permafrost engineering given at the University of Alberta.

Looking ahead, the CPA plans to develop prizes and awards in the broad field of permafrost study and to set up a charitable arm in order to provide further support for early career researchers. The CPA has also submitted a pre-bid to host the 2024 International Conference on Permafrost (ICOP) in Whitehorse.

Canadian permafrost research intensified dramatically over the past two decades, driven by a need to understand this fundamental element of the cryosphere. This trend continued during 2015-2018 and there is no sign of it reversing.

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SECTION E: LAKE ICE AND RIVER ICE
Report compiled by C. Duguay, University of Waterloo

Lake ice and river ice research in Canada (2015-2018)

The freshwater (lake and river) ice research community is a relatively small one compared to that of other components of the cryosphere. In Canada, freshwater ice research is conducted at a few academic institutions; mainly Institut National de la Recherche Scientifique (INRS; M. Bernier), University of Saskatchewan (K.-E. Lindenschmidt), University of Toronto (L. Brown) and University of Waterloo (C. Duguay), as well as at Natural Resources Canada (NRCan; J. van der Sanden) and C-CORE/Memorial University of Newfoundland. For the 2015-2018 reporting period, research activities have largely focused on technological developments (new approaches and algorithms) for the mapping/monitoring lake ice and river ice using remote sensing observations. Existing satellite-derived ice products (IMS and MODIS) or products generated from some of the novel algorithms have been used by Canadian researchers to document variability and trends in freshwater ice at both hemispheric and regional scales.

Research highlights (2015-2018)

1. Technological developments

A review of advancements in satellite remote sensing of lake ice and river ice (pre-2015) can be found in Duguay et al. (2015a). Between 2015 and 2018, simple (Beckers et al., 2017; Murfitt et al., 2018b) and more advanced numerical ice models, such as the Canadian Lake Ice Model (CLIMo; Duguay et al., 2003) (Gunn et al., 2015b; Surdu et al., 2015; Antonova et al., 2016; Kheyrollah Pour et al., 2017), have been used in support of the development of lake ice thickness and ice phenology (freeze-up, break-up, ice duration) retrieval algorithms from remote sensing. Progress has also taken place on the incorporation of ice-jam numerical modelling and geospatial tools as well of synthetic aperture radar (SAR) imagery to map and help predict flood hazard and vulnerability (Lindenschmidt et al. 2016; De Munck et al., 2017). In addition, both ground-based and satellite polarimetric observations of lake ice cover have provided new knowledge for the improvement of microwave radiative transfer models that include both snow and ice layers (Atwood et al., 2015; Gunn et al., 2015a). The sections below highlight some of the key contributions made by Canadian institutions, individually or in collaboration with international groups, over the past four years.

1.1 Remote sensing of lake ice

1.1.1 Ice cover extent and ice phenology

Mapping ice cover extent and ice dates (phenology) is important for improving weather forecasting and for climate monitoring (GCOS, 2016) in cold regions. Satellite remote sensing has assumed a greater role in lake ice observations in recent years due to the dramatic reduction in ground-based observational recordings and the availability of increasingly longer satellite datasets, particularly from 2000-onward (Duguay and Brown, 2018). Researchers have particularly been active in the development of retrieval algorithms (automated or semi-automated approaches) for the generation of ice products using data provided by the Canadian RADARSAT-2 SAR satellite (lakes on North Slope of Alaska by Surdu et al., 2005; lakes in Central Ontario by Murfitt et al., 2018a; Lake Erie by Wang et al.,

2018) and, to a lesser extent, passive microwave (AMSR-E/2) (lakes across the Northern Hemisphere by Du et al., 2017).

In preparation for the upcoming RADARSAT Constellation Mission (RCM; a constellation of three satellites), due for launch in mid 2019, work was also undertaken to assess the potential of compact polarimetry (CP) data to be delivered by RCM (simulated from polarimetric RADARSAT-2 data) for monitoring ice and open water during the break-up period (van der Sanden and Geldsetzer, 2015). It is anticipated that SAR will play a greater role in lake ice mapping/monitoring in the near future with the availability of data from both the European Space Agency's Sentinel-1A/B satellites and the Canadian Space Agency's RCM.

1.1.2 Ice thickness

Measurements of ice thickness are critical in support of winter transportation (e.g. shipping on the Laurentian Great Lakes and ice roads that serve northern communities) and recreational activities (e.g. snowmobiling and ice fishing). The measurements are also important for climate monitoring (GCOS, 2016). However, field measurements of ice thickness are generally lacking across Canada. Research has therefore investigated approaches to estimate ice thickness from active microwave (field-based scatterometry, satellite altimetry and SAR) and thermal remote sensing.

Gunn et al. (2015) acquired time series of ground-based X- and Ku-band frequency-modulated continuous-wave (FMCW) radar data to derive ice thickness for bubbled freshwater lake ice with heterogeneous snow cover at a lake site near Churchill, Manitoba. By investigating the distance between peak returns at the at the ice–snow and ice–water interface, they derived ice thicknesses with root mean square error (RMSE) values of 5.3 and 8.8 cm for X- and Ku-band, respectively, relative to in-situ measurements. Beckers et al. (2017) used the general approach proposed by Gunn et al. (2015) to estimate ice thickness on Great Bear Lake and Great Slave Lake (GSL) by exploring waveforms from CryoSat-2 (CS2) Ku-band radar altimeter. The study obtained ice thickness estimates with RMSE of 33 cm when compared to in-situ measurements obtained at GSL. Murfitt et al. (2018b) evaluated the application of RADARSAT-2 for estimating lake ice thickness in Central Ontario. They report RMSE values of 11.7 cm and attribute uncertainty to unexplored questions about scattering mechanisms and the interaction of radar signal with mid-latitude lake ice. In addition to the radar-based investigations described above, lake surface (ice/snow) temperature observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard the Terra and Aqua satellites have also been evaluated for estimating lake ice thickness (Kheyrollah Pour et al., 2017). Using heat balance terms derived from the lake ice model, CLIMo (Duguay et al., 2003), the authors were able to retrieve ice thicknesses up to 1.7 m from MODIS with RMSE of 17 cm and mean bias error of 7 cm when compared to field measurements acquired on GSL (NWT) and Baker Lake (Nunavut).

1.1.3 Observations of backscatter and brightness temperature, and radiative transfer modeling

It has been a long withstanding belief that the dominant microwave scattering mechanism of ice in shallow Arctic lakes is double-bounce scattering of columnar air bubbles and the ice/water interface (Duguay et al., 2005a). Also, the impact of surface ice type and on-ice snow depth on microwave signals (backscatter and brightness temperature) had not been well, if at all, documented to date. Major progress has been made by Canadian researchers and international collaborators in better understanding and modeling microwave scattering mechanisms of snow-covered lake ice with air bubbles (Atwood et al., 2015; Gunn et al., 2015; Gunn et al., 2017; Gunn et al., 2018).

Analyses of polarimetric (X, C, and L-band) SAR satellite and ground-based Ku and X-band scatterometer measurements, supported by radiative transfer modeling experiments, have revealed that the high backscatter of floating ice on shallow Arctic lakes is from the ice/water interface (due to appreciable surface roughness or preferentially oriented ice facets) and that the dominant scattering mechanism from that interface is single bounce rather than double-bounce (Atwood et al., 2015; Gunn et al., 2018. Furthermore, Ku and X-band scatterometer (HH and VV polarization) observations and modeled backscatter using dense medium-radiative transfer theory under the quasi-crystalline approximation (DMRT-QCA), which treats bubbles within an ice volume, have shown that Ku-band is sensitive while X-band is insensitive to snowpack overlying lake ice (Gunn et al., 2015). Gunn et al. (2017) indicate that X-band backscatter (VH in particular) and 19 GHz H brightness temperature observations are influenced by ice types (grey and rafted ice) which are not currently considered in microwave models.

1.1.4 Bedfast ice on shallow Arctic lakes

Radar remote sensing permits to distinguish lakes with bedfast ice due to the difference in backscatter intensities from bedfast (low return) and floating ice (higher return) (Duguay et al., 2015a). Antonova et al. (2016) have shown the potential of a unique time series of three-year repeat-pass TerraSAR-X (TSX) imagery with higher temporal (11 days) and spatial (10 m) resolutions than available in past studies for monitoring bedfast ice as well as ice phenology of lakes in the Lena River Delta, Siberia. Additionally, the authors analyzed an 11-day sequential interferometric coherence time series from TSX as a supplementary approach for the bedfast ice monitoring. Coherence time series were found to detect most of the ice grounding as well as spring snow/ice melt onset.

1.2 Remote Sensing of river ice

1.2.1 Ice formation, progression and deterioration

INRS and University of Saskatchewan have been leading much of the recent research on remote sensing and modeling of river ice in Canadian universities. Das et al. (2015) used RADARSAT-2 satellite and time-lapse camera imagery to understand the mechanisms of ice cover formation progression along the river during the course of winter. Time-lapse images allowed for the identification of frazil ice generation and patterns of stable ice cover formation during freeze-up (Slave River near Fort Smith), while RADARSAT-2 images (delta areas of the Slave) captured ice cover flooding due to higher river flows in mid-winter. Chu and Lindenschmidt (2016) built on this work to improve characterization of ice processes along the Slave River through a combination of MODIS near-infrared imagery for monitoring river ice phenology and mapping river ice cover extent, and RADARSAT-2 imagery for characterizing river ice thickness, ice types and seasonal changes of ice-cover characteristics. The authors found that the rate of river ice break-up is much faster than the rate of river freeze-up (analysis of MODIS imagery) and that RADARSAT-2 imagery can be used to successfully characterize and map various ice types (described below). In association with hydrometeorological parameters, the study revealed that the thermal deterioration of the ice cover during break-up appears to be the primary break-up event in the Slave River.

1.2.2 Ice characteristics and classification

Chu et al. (2015) developed a RADARSAT-2 based method to monitor the spatial and temporal patterns of ice covers and ice types during the freeze-up period along the main channel of the Slave River Delta. Through the analysis of backscatter and image texture (images acquired from November to March), the authors were able to determine four ice cover/water classes (consolidated ice, juxtaposed ice, thermal ice and open water). In a follow-up study, Chu and Lindenschmidt (2016) showed that RADARSAT-2 imagery can be used to characterize and map intact ice, smooth rubble ice, rough rubble ice and open water during the break-up period.

Researchers from Poland with their Canadian counterparts at INRS compared the value of RADARSAT-2 quad-polarization (Single Look Complex, SLC) to dual-polarization data to map ice types on two rivers - the Peace River in Canada and the Vistula River in Poland Los et al. (2018). They found that quad-pol data did not improve significantly the accuracy of the river ice classifications in comparison with the classifications made with dual-pol data. For the Vistula River, the authors could not discriminate contact zones between fields of smooth ice. However, they were able to distinguish other ice classes (smooth ice, juxtaposed and agglomerated ice cover that form from mobile ice). Consolidated ice on the Peace River and agglomerated ice on the Vistula River could equally be detected with quad-pol and dual-pol data (regardless of polarization channel combination). In the case of the Peace River, open water and skim ice could not be discriminated through classification.

1.2.3 Ice jams and flooding

In cold regions, river ice-jam flooding can be more severe than open-water flooding causing property and infrastructure damages, but little work has been performed to assess the risk induced by ice-related floods. Research at the University of Saskatchewan has been on the incorporation of ice-jam numerical modelling tools (e.g. RIVICE and Monte-Carlo simulation) into flood hazard and risk assessment with tests performed along the Peace River (Town of Peace River, Alberta) (Lindenschmidt et al., 2016). Work conducted at INRS has focused on the development of a geospatial (GIS-based) modeling tool to identify river channels most susceptible to ice jams from broken ice during break-up (De Munck et al., 2017). The approach uses six parameters previously reported to be potential causes of ice jams. They include presence of an island, narrowing of the channel, high sinuosity, presence of a bridge, confluence of rivers, and slope break. An ice jam predisposition index, which weights for the importance of each parameter, was tested for three rivers in the province of Québec. The authors report that 77% of the observed ice jam sites obtained from historical records occurred in river sections that the model considered as having high or medium predisposition of ice jamming.

2. Variability and trends in freshwater ice

2.1 Lake ice

Lake ice cover (extent) has been identified as an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS, 2016). Canadian researchers have been active contributors on lake ice to climate assessment reports for many years, including NOAA's Arctic Report Card (e.g. Duguay and Brown, 2018) and annual "State of the Climate" issues of the Bulletin of the American Meteorological Society (BAMS) (e.g. Duguay et al., 2015). They have provided annual updates on short-term trends and variability in lake ice cover phenology (freeze-up, break-up, and ice cover duration) for the largest lakes of the Northern Hemisphere (2004-onward) using the Interactive Multisensor Snow and Ice Mapping System (IMS) satellite-derived 4-km gridded binary (ice/no ice) product. In collaboration with U.S. scientists, they have also contributed to the analysis of a 12-year (2002–2015) ice record derived from AMSR-E/2 (5-km grid) revealing increasingly shorter ice cover duration for 43 out of the 71 largest lakes of Northern Hemisphere (Du et al., 2017); higher-latitude lakes showing more widespread and larger trends toward shorter ice cover duration than lower-latitude lakes, consistent with observed Arctic warming.

The more pronounced response of Arctic lake ice to enhanced polar warming has been the topic of an investigation by researchers at the University of Waterloo (Surdu et al., 2016). In a study that focused on the analysis of a 15-year time series (1997–2011) of RADARSAT-1/2 ScanSAR Wide Swath, ASAR Wide Swath and Landsat images from 11 lakes located in both polar-desert and polar-oasis environments, the authors showed that ice melt onset has been occurring earlier for all lakes and that some lakes may be transitioning from a perennial/multiyear to a seasonal ice regime. At more southern latitudes (Ontario and Manitoba), researchers at the University of Toronto (Murfitt and Brown, 2017) have investigated lake ice phenology dates derived from MODIS (MOD10A1 Snow/Ice 500-m product) in relation to recent trends in temperature and 0 °C fall and spring isotherms (2001-2014). Their study found that ice-on and ice-off dates generally shifted with the 0 °C isotherm dates, demonstrating that the ice phenology of lakes in Ontario and Manitoba, Canada, is responding to short-term variability in temperature.

2.2 River ice

Investigations on trends and variability in river ice phenology and dynamics are less common than they are for lake ice. Muhammad et al. (2016) developed an approach for estimating ice break-up dates on the Mackenzie River (MR) using MODIS (MOD/MYD10A1 Snow/Ice 500-m product), complemented with 250 m Level 1B radiance products (MOD/MYD02QKM) from the Terra and Aqua satellite platforms. Analysis of these products allowed the researchers to identify melt onset and end dates along the MR as well as melt processes driving ice break-up (thermodynamically or dynamically driven). The authors documented variability in break-up dates using MODIS data from 13 ice seasons (2001–2013), showing melt initiation occurring on average between day-of-year (DOY) 115 and 125, and ending between DOY 145 and 155, resulting in an average melt duration of ca. 30–40 days. Muhammad et al. (2016) showed that channel morphology is a more important control of ice break-up patterns than previously believed with ice runs on the MR strongly influenced by channel morphology (islands and bars, confluences and channel constriction).

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SECTION F: CRYOSPHERIC DATA MANAGEMENT AND ARCHIVE

Report compiled by: Wesley Van Wychen, University of Waterloo

The Polar Data Catalogue, University of Waterloo (Wesley Van Wychen).

Since its inception in 2007, the Polar Data Catalogue (PDC) is Canada's premier data management solution for Arctic, Antarctic and Cryospheric researchers. The ongoing mandate of the PDC is to ensure the long-term integrity of "Polar" metadata and datasets to make these available to the public, to policy-makers, to researchers, and crucially, to Northerners and Northern communities. The PDC's data repository is interdisciplinary by nature, reflecting the wide diversity of research being undertaken in both the Arctic and Antarctic. As such, the records housed within the PDC cover a wide range of disciplines from earth observation, natural and biological science to policy health and social sciences.

In recent years, the PDC has focussed on several key items, including; refreshing its enterprise-grade server infrastructure in order to ensure the continued integrity for metadata and data records stored within the PDC, updating the suite of PDC's online webtools (available at www.polardata.ca) to better facilitate metadata and data deposit and search (especially for low-bandwidth users), investigating the implementation of new technologies and data management solutions (including the potential for cloud-based storage and data processing), working toward ensuring interoperability between the PDC and other data repositories, and promoting the importance of Polar data stewardship both nationally and internationally. All of this work continues and builds upon PDC's legacy of providing robust, standards compliant data management solutions to the Arctic and Antarctic research communities.

Recent Publications:

Church, D. L., Friddell, J. E. and Le Drew, E. F. (2016), The Polar Data Catalogue: A Vehicle of Collaboration, Northern Community Partnerships and Policy-Making. Arctic Yearbook, available online: <https://arcticyearbook.com/arctic-yearbook/2016/2016-briefing-notes/202-the-polar-data-catalogue-a-vehicle-for-collaboration-northern-community-partnerships-and-policy-making>

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