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SUMMARY OF PROPOSAL FOR PUBLIC RELEASE (Use plain language.)

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Northern Hemisphere sea ice and seasonal snow cover are retreating at an unexpectedly rapid rate, presenting a range of impacts and challenges to Canada and the world. Recent research connects Northern Hemisphere sea ice and snow to global weather, to streamflow and soil moisture in mountainous regions like the Fraser River Basin, to critical parts of economic infrastructure in Canada's North, and to many aspects of anthropogenic climate change. There is thus an urgent need to improve and exploit scientifically grounded predictions on seasonal snow cover, sea ice, and the climate elements they are linked to. There is also a need to assess the drivers of recent snow and sea ice trends to better anticipate their future evolution. The Canadian Sea Ice and Snow Evolution Network (CanSISE) assembles leading Canadian and international expertise in state of the art observational analysis and computer models of climate. The Network partners University and Environment Canada climate scientists, students, and other trainees. It aims to advance prediction of snow and sea ice in the Arctic, sub-Arctic, alpine, and seasonally snow covered regions, with a primary focus on the Canadian Arctic and the Western Canadian Cordillera. It will assess how well Environment Canada's climate models simulate snow and sea ice and their linkages to global climate, and use new sources of data, new modelling and prediction methods, and new physical insights into snow and sea ice processes to improve climate predictions. The Network will provide authoritative forecasts on snow cover, sea ice, alpine spring freshet, and related aspects of cold-region climate in the next and subsequent decades. Looking retrospectively, it will also quantify statistically the likelihood that recent extremes, like the Arctic sea ice loss events in 2007 and this year, are caused by human activity. Finally, CanSISE will help design the next generation of observational campaigns in Canada to obtain the data that most effectively improves snow and sea ice prediction. CanSISE will provide a more confident assessment of the future of the Canadian Arctic and sub Arctic climate, and train a new cadre of researchers prepared to undertake climate prediction in an era of rapid cryospheric change.

Other Language Version of Summary (optional).

La glace et la neige saisonière de l'hémisphère nord reculent à un taux accéléré, présentant des impacts et défis au Canada et le monde entier. Des études récentes lient la glace et la neige de l'hémisphère boréal au temps, l'écoulement des rivières, et l'humidité du sol dans les régions montagneuses, et plusieurs aspects des changements climatiques anthropiques. Il y a donc un besoin urgent d'améliorer et d'exploiter des prévisions de la neige saisonière, la glace marine, et les éléments du climat auxquels ils sont liés ainsi qu'un besoin d'analyser les causes des récentes tendances du couvert neigeux et de la glace afin de mieux anticiper leurs changements futurs. Le Réseau de l'Évolution de la Neige et la Glace Marine au Canada (RENGMC) rassemble des chercheurs éminents Canadiens et internationaux avec expertise sur les analyses d'observations et modèles numériques du climat. Le Réseau regroupe des chercheurs, étudiants, et autres stagiaires du milieu universitaire et d'Environnement Canada. Son objectif est d'améliorer les prévisions de la neige et la glace marine dans l'Arctique, les régions sub-arctiques et montagneuses, avec un accent sur l'Arctique canadien et la Cordillère de l'ouest du Canada. Une évaluation de la performance des modèles numériques d'Environnement Canada à simuler la neige et la glace marine et leurs liens au climat global sera entreprise tout en utilisant de nouvelles données, des modèles et méthodes de prévisions innovatrices, et des aperçus sur les processus physiques mèneront à une meilleure prévision du couvert neigeux et de la glace marine. Avec une perspective sur le passé, le Réseau va quantifier les probabilités que des extrêmes récents, tel que le minimum de glace en 2007 et encore cette année, sont causés par des activités humaines. Finalement, le RENGMC va préparer la conception de futures campagnes d'observation au Canada afin d'obtenir les données qui améliorent le plus efficacement les prévisions de la neige et la glace marine. Le Réseau va produire des analyses plus fiables de l'Arctique canadien et du climat sub-Arctique, et entraîner la nouvelle génération de chercheurs qui entreprendront les prévisions climatiques au milieu d'un environnement changeant rapidement.

<u>Can</u>adian <u>S</u>ea <u>I</u>ce and <u>S</u>now <u>E</u>volution: The CanSISE Network

Section 1. INTRODUCTION

Section 1a. Background and Objectives

[*Note that in this proposal, acronyms will be introduced in* **BOLD**.]

This proposal seeks support for *The Canadian Sea Ice and Snow Evolution Network* (**CanSISE**), a new Canadian climate research network to advance observation, prediction, and understanding of seasonal snow cover and sea ice (**S/SI**) in Canada and the circumpolar Arctic. CanSISE is concerned with evolution of S/SI over the past century and in the coming seasons, years and decades, in light of climate variability and anthropogenic climate change. The basic research that will be described below is relevant to domains of application impacted by variability and change in S/SI. These include, but are not limited to, cold-climate ecosystems and ecosystem services, recreational activities, natural resource exploration and extraction, hydroelectric generation, hunting and agrculture, and transportation. These wide ranging applications reflect the importance of S/SI to Canada's environment, economy, and identity. This importance is also reflected by historic public funding support of S/SI research. Recent climate events provide urgent motivation for renewal of such support: Northern Hemisphere spring seasonal snow cover has set several record lows since 2008 (Derksen and Brown, 2012) and Arctic SIE has in September 2012 attained its lowest seasonal minimum extent in the satellite era, shattering the previous record low of 2007 (National Snow and Ice Data Center report, September 2012). Canada's climate scientists are being asked to explain and put in context such events, but it remains challenging to do so. For example, while greenhouse warming is almost certainly a driver for these changes, current climate models have difficulty realistically capturing them (Derksen and Brown 2012; Stroeve et al. 2007). Given the importance of S/SI, demands for confident assessments of S/SI events, and remaining research unknowns, we believe that supporting this network's proposed programme of S/SI research and associated deliverables is critical to Canada's short- and long-term strategic interest.

CanSISE is motivated by the overarching scientific challenge of understanding, simulating, and predicting S/SI on seasonal to multidecadal scales. On these timescales, S/SI are coupled to variability in the atmospheric and ocean circulation and to hydrological variables like runoff and soil moisture. (Permafrost and land ice variations and their climate interactions, not considered here, are more prominent on multidecadal and longer timescales.) S/SI processes and their climate couplings are highly challenging to understand and simulate. For example, the distribution of Arctic sea ice is sensitive to large scale atmospheric surface flow, which is difficult to represent consistently in reanalysis products and in climate models; and there is a wide range in how models represent the coupling between snow albedo and surface temperature (Section 2c and references therein). S/SI are also challenging to characterize observationally owing to sparse surface observations and difficulty in retrieving many S/SI variables from raw satellite measurements. In addition, S/SI trends can be masked by decadal variability, which is larger at high latitudes. One consequence of this is that long term observational data sets for snow cover have only recently been reconciled, and considerable observational uncertainty remains (Brown et al. 2010).

Balancing these science challenges with the potential payoffs of improved S/SI prediction, Canada and the international community have begun to invest significant research and operational resources into developing practical prediction systems capable of forecasting S/SI and related hydroclimate impacts. On seasonal to subdecadal timescales, advances in such systems could improve prediction skill in circulation and hydrological variables that are in part driven by S/SI (e.g. Barnett et al. 2008, Cohen and Fletcher 2007, Section 2a of this proposal). On decadal to multidecadal timescales, improved S/SI process representation is required for accurate projections of global climate change (e.g. Flanner et al. 2011, Section 2c). (Climate model *predictions* derived from observed initial conditions and time evolving radiative forcings are distinguished here from *projections* that do not use observed initial conditions.) Furthermore, improved understanding and prediction would assist in the interpretation of S/SI variability and their responses to anthropogenic forcing (e.g. Min et al. 2008b, Section 2b).

CanSISE proposes to analyze and further develop these climate prediction systems with a focus on S/SI, via a programme of carefully planned and coordinated research. More specifically, **in the CanSISE Network, Environment Canada (EC) and University researchers will seek to advance seasonal to multidecadal prediction of S/SI in the Arctic and in Canada's sub-Arctic, alpine, and seasonally snow covered regions; and to quantify and exploit for prediction purposes the role that Northern Hemisphere S/SI processes play in climate variability and change.** Besides EC, CanSISE will partner with the **Pacific Climate Impacts Consortium** (**PCIC**) and with the **Canadian Ice Service** (**CIS**). CanSISE will integrate expertise in climate analysis, S/SI modeling, and S/SI observations. It will serve to train the next generation of climate scientists in analysis of S/SI processes in climate simulations and observations. The proposed activity aligns well with priorities of the Government of Canada (**GoC**), as well as Research Themes 1–3 ("processes", "prediction", "Arctic") called for in the Climate Change and Atmospheric Research (**CCAR**) program. It will require an approximate $760K p.a. financial commitment, over 90% of which is budgeted for compensation of Highly Qualified Personnel (**HQP**; see Section 6).

The research proposed here is well integrated with Canadian and international efforts in S/SI research. For example, EC has developed models and produced simulations to contribute to international programmes such as the World Meteorological Organization's (**WMO**) World Climate Research Program (**WCRP**) Coupled Model Intercomparison Projects Phases 3 and 5 (**CMIP3** and **CMIP5**), and the WCRP Climate-system Historical Forecast Project (**CHFP**). In addition, the proposed modeling activities will be based on analysis of a rich, and in our view underexploited, S/SI observational archive developed largely by EC under the auspices of the International Polar Year (**IPY**) programme. The above modelling efforts have spurred in turn the development of the Canadian Seasonal to Interannual Prediction System (**CanSIPS**), which is now operational and whose improvement will be a primary focus of CanSISE in Research Area A (Section 2a). CanSIPS is the primary modelling tool for the federally funded Beaufort Regional Environmental Assessment (**BREA**), which focusses on seasonal climate prediction for the energy sector in the Beaufort region, and so improvement in CanSIPS will benefit follow on projects to BREA. Assessments of model S/SI simulation (Deliverable 1), the decadal prediction of S/SI (Deliverable 2), and the assessment of anthropogenic influence for the 2007 and 2012 sea ice loss events (Deliverable 3) will provide input to the next WMO Intergovernmental Panel on Climate Change 6th Assessment Report (**IPCC AR6**). Observational Deliverable 4, which will use the modelling outcomes of the Network to help design future observational campaigns, will provide EC with input to the WMO's Global Cryosphere Watch (**GCW**) Program. Finally, process studies on snow albedo in Research Area C and Deliverable 4 will contribute to the Arctic Council's Arctic Monitoring and Assessment Program (**AMAP**), which includes a focus on short term radiative forcing by black carbon. Further integration of the research outcomes of CanSISE with our partners and other Canadian and international partnerships will be discussed in Sections 3, 4, and 5.

Section 1b. Research approach, composition of research team, and structure of proposal

The CanSISE Network will analyze S/SI and related climate processes, motivated by the potential for current global climate models (**GCM**s) to capture these processes realistically on seasonal to multidecadal scales, by current efforts to develop Canada's seasonal to decadal prediction capabilities, and by the opportunity to employ underexploited observational resources in this analysis. Principal regions of interest include the Arctic, the Canadian sub-Arctic, the Western Cordillera of Canada, and Canada's seasonally snow covered areas.

Model resources: A particular interest of the Network is to evaluate and assist in improving representation of S/SI in EC's Canadian Centre for Climate Modelling and Analysis's (**CCCma**) GCMs. These GCMs include the coupled ocean-atmosphere climate model **CanCM4**, its atmospheric component **CanAM4**, and its Earth-System Model counterpart, **CanESM2**, which includes prognostic carbon dioxide and biospheric processes. CanSISE will also analyze versions of the model under development, as determined by CCCma staff, including the version of the CanCM system with the Nucleus for European Modelling of the Ocean (**NEMO**) ocean-sea ice model, which is anticipated to begin production during the second half of the Network. The Canadian GCMs will be analyzed in the setting of the existing CHFP, CMIP3, and CMIP5 model archives. These archives include long term simulations with initial conditions unconstrained by observations and forced with time evolving radiative forcings, and seasonal and decadal predictions initialized from estimates of observed climate states. In addition, CanSISE will analyze dedicated supplementary integrations of the National Centre for Atmospheric Research (**NCAR**) Community Climate System Model 4 (**CCSM4**) and Community Earth System Model 1 (**CESM1**) and the National Oceanographic and Atmospheric Administration (**NOAA**) Geophysical Fluid Dynamics Laboratory (**GFDL**) atmospheric GCMs **GFDL AM2** and **AM3**; these will be carried out at Toronto on the Compute Canada **SciNet** facility. Finally, the CanSISE Network's international collaborators will commit to coordinated integrations of their models for selected projects (**CNRM-GAME** [LT] and **UKMO HaGEM** [JS]; see Research Areas A and C). In addition to the global models, CanSISE will employ hydrologic models to study the hydrologic impacts associated with simulated and predicted variability and change.

Observational resources: CanSISE proposes to contribute significantly to the development of enhanced observational time series through the use of new datasets featuring novel retrieval methods and improved characterization of uncertainty. These data resources include: i) recent satellite derived datasets comprising snow cover extent (**SCE**), snow water equivalent (**SWE**), sea ice concentration (**SIC**), and sea ice type and area flux; ii) measurements from observational campaigns such as sea ice thickness (**SIT**) from airborne surveys across the Arctic; and iii) other observational data from the IPY programme. These datasets will inform future observational programs and will be used in models to explore the impact of improved S/SI information on prediction and process understanding of S/SI and related variables.

Research team: The CanSISE research team consists of 23 researchers, 12 of whom are applying for funding in this call. The team includes expertise in i) global climate dynamics and modelling, including analysis of S/SI feedbacks and connections to global climate variability; ii) acquisition and analysis of observational S/SI data, including remote sensing and field-based data; iii) statistical climatology for trend analysis, detection and attribution of climate signals, and linkages of climate drivers to hydrological impacts. The team consists of:

- Principal investigators (CanSISE Steering Committee, partners seeking funding in this call): P. Kushner, Toronto (**PK**); C. Derksen, EC (**CD**); S. Déry (**SD**), UNBC; J. Fyfe, EC (**JF**); C. Haas, York (**CH**); W. Merryfield, EC (**WM**); F. Zwiers, Victoria (**FZ**).
- Canadian co-applicants (funded partners): A. Berg, Guelph (**AB**); C. Fletcher, Waterloo (**CF**); N. Gillett, EC (**NG**); W. Hsieh, UBC (**WH**); B. Tremblay, McGill (**BT**)
- Other Canadian collaborators (unfunded partners): S. Bélair, EC (**SB**); G. Boer, EC (**GB**); R. Brown, EC (**RB**), EC; G. Flato, EC (**GF**, who is another member of the CanSISE Steering Committee); S. Howell (**SH**), EC; S. Kharin, EC (**SK**); M. Sigmond, Toronto (**MS**); X. Zhang, EC (**XZ**);
- International collaborators: J. Screen, U. Exeter, UK (**JS**); S. Son, Seoul U. (**SS**); L. Terray, Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (**CERFACS**), Toulouse, France (**LT**).

Advisory panel: In addition, CanSISE has formed an Advisory Panel whose purpose will be to advise the CanSISE steering committee on the development of key scientific issues and approaches that are central to CanSISE S/SI research. The panel consists of C. Bitz, Washington (**CB**); D. Lettenmaier, Washington (**DL**); T. Markus, National Aeronautical and Space Administration (**TM**, NASA); D. Pierce, Scripps (**DP**); and D. Smith, United Kingdom Meteorological Office (**DS**, UKMO).

Organization of proposed projects and HQP plans: The proposal is structured around three distinct but related *Research Areas* (A through C, Section 2) in which research projects will take place. These Research Areas feature a mix of basic science intended to lead to original scholarship and applications intended to lead to improvements in prediction systems and observational analysis. These Research Areas are described in Section 2; the descriptions include brief work plans and indicators of who will carry out the work. The research described in Section 2 will culminate in four *Deliverables* (1 through 4, Section 3). Each Deliverable provides a summary assessment on a topic of importance to the partners in the proposal (EC, PCIC, and CIS). Applicants and collaborators are identified by initials like "**PK**" according to the lists above. HQP are indicated in the work plan text according to labels like "**PHD01**". Details of the HQP are provided in the Budget Justification HQP table and further descriptions of the activities undertaken by the network are provided in the Form 101 Activity Schedule.

Section 2. RESEARCH AREAS

The following describes three related lines of S/SI research that will represent the main activity of CanSISE. Research Area A involves an effort to bring together state of the art models and observations to improve prediction of S/SI and related variables (Section 2a). Research Area B involves an assessment of Canadian and circumpolar Arctic S/SI and climate evolution over the last several decades to determine the extent to which recent S/SI trends and extreme events are the result of human influence (Section 2b). Finally, Research Area C involves an evaluation of S/SI processes and their related climate linkages in current climate simulations (Section 2c). The Research Areas will be coordinated by Canada's top scientists in the field and are composed of talented teams drawn from the University and GoC laboratory environments (see Section 4a). The work in the three Research Areas will proceed in parallel with a schedule organized around three Network Workshops that are described in Section 6.

Section 2a. Area A: Seasonal to Multidecadal S/SI Prediction and Projection (Lead: WM)

Dynamical climate prediction is a rapidly developing science that is yielding significant societal benefits as well as contributing to an improved understanding of the climate system. The application of coupled climate models to climate prediction is a relatively recent development that has greatly expanded the potential capabilities of prediction systems by enabling a broad array of climate system variables (atmosphere, ocean, land, sea ice) to be forecast and by extending the forecast range to a decade or more. However promising, these extended capabilities of dynamical climate prediction systems are only beginning to be identified and their utilities explored. In particular, dynamical prediction of S/SI, and the cryosphere more broadly, is a nascent area where concentrated research is likely to yield rapid advances. The dramatic changes currently occurring in the cryosphere lend a further element of timeliness to such efforts.

Area A is directed toward advancing fundamental aspects of S/SI prediction, primarily through analyses of existing climate simulations and observational data. Although evaluating existing predictive capabilities is important, realizing the full value of such results requires synthesizing available observational knowledge into datasets that can be used to validate model predictions, as well as assessing the natural limits to climate predictability so that the degree to which available predictability is being realized can be quantified. The new observational products, will have valuable further applications including characterizing historical S/SI trends and variability together with their causes and influences as examined in Area C. Conversely, improved understanding of local and teleconnected S/SI influences obtained from Area C will aid in identifying sources of predictive skill in forecasts where these processes are represented adequately, and point toward avenues for improving forecasts in cases where they are not.

The four projects of Area A encompass the fundamental aspects of dynamical prediction: observational data for verification, evaluation of predictions, and predictability. The evaluation component is divided according to prediction range: monthly to multi-seasonal vs interannual to multidecadal, which reflects the differing datasets, methodologies and applications in these two regimes.

Project A1 Improved observational datasets for initialization and verification of S/SI predictions (CD, CH, SB, RB, WM): Advancement of S/SI prediction has been impeded by a scarcity of homogeneous observational datasets for initializing forecast models and verifying predictions. The need for such products will be addressed through two complementary channels. In the first, state-of-the-art observational time series will be compiled for SCE (using NOAA snow chart Climate Data Record [CDR, Brown and Robinson 2011] and reanalysis based proxies), SWE (using the European Space Agency [**ESA**] GlobSnow product [Takala et al. 2011] and the Canadian Meteorological Centre [**CMC**] gridded analysis [Brasnett 1999]), sea ice extent (**SIE,** using the NASA Team 2 and Canadian Ice

Service Digital Archive [**CISDA**] products), and sea ice flux (using EC IceTracker applied to Radarsat archive and ESA GlobIce products, and drifting buoys) along with unique field observations that provide important 'snapshots' (airborne SIT measurements from NASA IceBridge campaigns and from CanSISE member CH; upward looking sonar; ICESat ice and CryoSat SIT products). A point of emphasis will be the use of multiple datasets focused on the same variable (as in Brown et al., 2010) in order to improve error characterization through observational time series. The role of emerging observational products, such as sea ice thickness datasets from satellite altimeter measurements (i.e. CryoSat-2) will also be explored. The second approach will involve extending time series from the Canadian Land Surface Data Assimilation System (**CaLDAS**) backward in time, ideally to 1981, which is the initial year of the CanSIPS verification period. These two approaches are complementary because the first gathers data from a wide range of sources including historical field campaigns, whereas the second processes data products that are available in near-real time into an operationally-realizable analysis. This project provides essential input to Projects A2 and A3, as well as to determination of CanCM4/ESM2 biases in Area C, and ultimately to the assessments in Deliverable 1.

EC-PDF01 and **U-PDF10** will compile state of the art observational datasets for snow and sea ice, with error estimates, and formatted to enable their application to forecast initialization and validation. CD, CH, RB and WM will assist in guiding these efforts and interpreting results. **U-PDF04** will extend CaLDAS land analysis to earlier years under guidance of SB.

Project A2: Assessing and improving monthly to multi-seasonal S/SI and related predictions: The primary basis for this project is CanSIPS, which produces multi-seasonal ensemble climate forecasts (1-12 month range) by running two versions of the CCCma coupled climate model, CanCM3 and CanCM4, from initial states constrained by atmospheric, ocean and sea ice observations (Merryfield 2011, 2012). CanSIPS became operational in December 2011 and since then has provided EC's monthly to multi-seasonal climate forecasts. A comprehensive set of CanSIPS hindcasts, initialized each month from 1979 through 2011 and including daily and monthly mean values of many climate variables including winds, surface fluxes, sea ice, snow and soil moisture, etc. are available for analysis.

The general aims of this project are to evaluate CanSIPS skill for predicting S/SI and related variables, to assess the contribution of S/SI initialization to climate prediction skill, to improve S/SI initialization in CanSIPS utilizing observational datasets developed under Project A1, and develop related applications such as downscaled sea ice predictions for Canadian ice covered waters (in cooperation with CIS) and the prediction of streamflow in Canada's Western Cordillera. Anticipated outcomes will include forecast methodologies specific to S/SI, improved knowledge of the capabilities and deficiencies of the current system in representing and predicting S/SI, and an expanded range of CanSIPS-related products and applications. Specific proposed activities are as follows:

A2.1: Assessment of prediction skill for S/SI and related variables in CanSIPS hindcasts based on current and enhanced verification datasets (CD, CH, SH, SK, MS, RB): This will involve the determination of appropriate skill measures for forecast fields relating to sea ice and snow over the 12-month forecast range. Determinations based on currently available verification datasets will be undertaken first: these include SIC from the satellite passive microwave record (1979-present, housed at the National Snow and Ice Data Center [**NSIDC**]; Steffen et al., 1991) and the Hadley Centre Sea Ice and Sea Surface Temperature data set [**HadISST**] dataset which uses historical conventional observations to extend the time series back to the late 19th century (Rayner et al, 2003); Northern Hemisphere SWE from ESA GlobSnow and the CMC daily gridded analysis; and Northern Hemisphere SCE from the NOAA CDR. Skill determinations will then be repeated when improved gridded data products from Project A1 become available. Because observational errors can be detrimental to measurements of forecast skill, we anticipate that calculated forecast skills might be enhanced by the improved verification data. Forecast skill will further be compared to predictability results from Project A4 with a view to identifying processes that limit forecast skill in regions where predictability is evident. Skill determinations for additional fields such as SIT and sea ice motion may be enabled by the new datasets if sufficient coverage for those fields can be attained.

EC-PDF01 (supervised by CD, focused on snow cover) and **U-PDF10** (supervised by CH, focused on sea ice) will compile state of the art observational time series (including quantified uncertainty) and perform assessment of CanSIPS predictions. The sea ice evaluation activities will be connected to operational collaborators at the CIS. **EC-PDF01** and **U-PDF10** will validate the prediction of snow and sea ice variables in CanSIPS hindcasts using standard datasets available prior to CanSISE, and the enhanced datasets produced for A1. CD, CH, SH and RB will aid in interpreting the results, with guidance relating to appropriate skill measures being provided by SK.

A2.2: Improved CanSIPS snow/land surface initialization (WM, AB, SB): One promising avenue for improving Canadian sub-seasonal, seasonal, and longer time scale dynamical forecasts is by constraining snow and other land surface variables directly through assimilation of observationally-based data products, rather than indirectly through the models' data-constrained meteorology as is currently done. This activity will develop methodologies for improved land initialization that can be applied in near-real time, enabling their potential operational use. Two land data products will be examined: i) the existing Guelph global land analysis which is based on the Canadian Land Surface Scheme (**CLASS**), which is the land component of the CCCma models, forced by bias corrected reanalysis products (Berg et al. 2003, 2005); and ii) CaLDAS, which assimilates satellite and other data products available in near-real time. The variables, resolution and methodologies employed for CaLDAS differ from those of Guelph/CLASS/CCCma data, and so a necessary step will be to develop transformation and scaling algorithms to enable assimilation of CaLDAS products into the CCCma models. This will be informed by intercomparison/validation of Guelph and CaLDAS fields focusing on snow, which strongly influences soil moisture in spring, as well as soil moisture itself. Following this, several sets of ensemble forecasts will be performed that incorporate Guelph and CaLDAS analyses into the land initial conditions. Forecast skills will be assessed against those for the currently employed land initialization, and compared against those of comparable sets of forecasts where land initial conditions have been "scrambled" by employing fields for the correct date but a different randomly selected year as in the international Global Land Atmosphere Coupling Experiment 2 (**GLACE-2**) project (Koster et al. 2010, 2011; Drewitt et al. 2012).

EC-PDF04 will assess how well current CanSIPS initialization procedures represent snow variables (SCE and SWE) in terms of initialization errors and ensemble spread, and examine the temporal dynamics of their forecast error growth in relation to physical processes and model biases. **PHD03** will evaluate snow variables and the role of albedo feedbacks in the off-line CLASS simulation. **U-PDF03** will assess influences of snow initialization on CanSIPS skill through GLACE2-like experiments, whereas **U-PDF04** will develop means to rescale CaLDAS variables for CanSIPS initialization and assess their influences on forecasts. AB, SB and WM will guide this work.

A2.3: Improved CanSIPS sea ice initialization (CH, CD, SH, WM, GF): Improved sea ice data products developed under Project A4 will be applied to initialization of sea ice, and an improved initialization procedure for ice thickness, which is poorly constrained in the current implementation of CanSIPS, will be developed based on empirical relationships between ice thickness and prior evolution of SIC. Impacts on sea ice forecast skill will be assessed through a limited set of forecast case studies including the 2007 and 2012 ice minima. The procedure will be implemented in a future CanSIPS version if indications of skill improvement are found.

PHD10 working with WM will develop and validate statistically-based ice thickness reconstructions based on results of A3. **U-PDF12** working with CH and WM will develop means for assimilating ice thickness observations into reconstructions, and evaluate the effectiveness of these thickness fields with and without assimilation for initializing CanSIPS forecasts. **UPDF-10** with CH will carry out the sea ice forecast skill assessment.

A2.4: Streamflow predictions based on statistically downscaled CanSIPS forecasts (WH, FZ, SD, WM): Streamflow predictions for Canada's Western Cordillera have important applications for estimating future hydropower generation potential, flood risks, etc.. Most existing streamflow prediction models obtain their skill mainly from observational estimates of the state of the snowpack at the start of the forecast, without taking into account any future climatic deviations from historical means. The ability of dynamical seasonal forecast systems such as CanSIPS to predict large scale, near-term climate anomalies with some skill suggests that such forecasts could potentially be employed to improve predictions of streamflow, provided one has a means for downscaling climate model predictions to the complex, mountainous terrain of the streamflow model.

This project aims to improve streamflow predictions in this way using a state-of-the-art Variable Infiltration Capacity (**VIC**) macroscale hydrology model (Liang et al. 1994; Wood and Lettenmaier 2006), employed also in project B3 and already in use at PCIC and UNBC, enabling previous model development to be leveraged for new research. In order to downscale the CanSIPS forecasts, nonlinear machine learning/statistical models (Hsieh 2009), trained on the CanSIPS hindcasts, will be developed to produce high-resolution bias-corrected SWE seasonal forecasts for input into the VIC model. Another requirement will be to skillfully initialize SWE which is a significant challenge due to the sparseness of in situ observations and the reduced utility of passive microwave remote sensing for the forested, complex terrain and wet snow that characterize this region. Two approaches will be taken to developing skillful SWE initialization for the 1/16 degree (~ 8 km) VIC model. The first will initialize SWE by calibrating retrievals from 25 km resolution passive microwave satellite observations against in situ SWE observations using advanced statistical methods that account for terrain and vegetation covariates. The second approach will apply such methods to the 15 km extended CaLDAS analysis produced under A4. These high-resolution SWE datasets will also be used for downscaling the CanSIPS forecasts.

PHD09 supervised by WH will develop nonlinear machine learning methods to downscale SWE in gridded observational products (microwave satellite data and CaLDAS) and CanSIPS forecasts. **Res. Assoc. 2** working with FZ will assess this and other downscaling techniques appropriate for driving the VIC hydrological model with reanalyses and climate model simulations. **U-PDF08** working with SD and FZ will examine the impact of historical air temperature and precipitation variations and trends on the VIC snow and streamflow simulations.

Project A3: Analysis of interannual to multidecadal S/SI predictions and projections (PK, CD, JF, RB, CH, GF, BT, GB, SK, MS, JS): Project A3 examines modeled S/SI behavior on time scales of year to decades, using CMIP5 short-term (“decadal”) predictions and long-term climate projections. This project will analyze (i) the ability of initialized decadal predictions vs uninitialized historical simulations to represent past changes in S/SI, and (ii) predictions and projections of future S/SI change, particularly over the next decade, informing Deliverable 2. Initial input for these studies will be existing CCCma decadal predictions based on CanCM4 and uninitialized historical simulations and projections based on CanCM4 and its earth-system model counterpart CanESM2. In order to sample over a range of model physics and initialization schemes, CMIP5 simulations from additional modelling centres will also be utilized. These CMIP5 simulations will be reevaluated against the improved observational products from Project A4 when the latter become available.

A further aim of Project A3 will be to adapt a pair of novel post-processing techniques, developed previously at CCCma to improve confidence in and quality of decadal predictions of global temperature, to Arctic SIE and other S/SI variables. The first such procedure improves the determination of decadal trends by removing estimates of higher frequency signals attributable to influences such as volcanic forcing and ENSO (Fyfe et al. 2011), whereas the second corrects for model biases in representing long-term trends in addition to the usual correction for biases in the climatic mean (Kharin et al. 2012).

An additional activity will examine influences of modeled low frequency (decadal to multi-decadal) ocean variability primarily in the North Atlantic on Northern Hemisphere sea ice. One motivation is that a subset of the CCCma decadal predictions that use a particular initialization technique have been found to be very skillful at predicting (analysed) North Atlantic overturning up to a decade in advance. Based on known relations this should translate to skill in predicting North Atlantic sea surface temperatures as well as surface air temperatures in, and ocean heat transport into, the Atlantic sector of the Arctic. Relations between these influences will be examined in CCCma decadal predictions to determine if such skill is realized.

Finally, we will estimate the relative role of forced and initialized S/SI predictability on timescales up to a decade. Hoerling et al.'s (2011) AGCM based method to estimate the decadal timescale climate response to radiative forcing over continental regions will be used. This method first estimates the pattern of oceanic SST response to radiative forcing from observations using the temporal optimal detection technique of Ribes et al. (2010) and then forces AGCMs with this SST pattern to obtain a forced teleconnected response. Large ensembles and multiple models reduce climate noise and produce a robust response in temperature and hydrological variables. The estimate of the forced signals is constrained to be close to observed SST trends, which helps overcome the difficulty that coupled ocean atmosphere models have in capturing the teleconnected climate response associated with tropical SST changes (Shin and Sardeshmukh 2011). Hoerling et al. (2011) provide only a prediction of the forced component for the period 2011-2020. We will evaluate this method in a hindcast setting (years 1981-1990, 1991-2000, etc.) with a focus on S/SI parameters and related climate variables. These integrations will be carried out with the atmospheric component of CanCM4 from EC, NCAR CAM4 and CAM5 at the University of Toronto using the SciNet computational facility, and the atmospheric components of CNRM-GAME and UKMO HadGEM (with LT and JS). Because sea ice loss strongly influences Arctic and sub-Arctic coastal responses (Deser et al. 2010, Hoerling et al. 2011), a significant component of this project will involve developing a suitable sea ice perturbation field for the hindcast periods, which will represent an estimate of the radiatively forced sea ice perturbation.

PDF01 co-supervised by PK and CD in Years 2-3 will analyze the roles of forcing and initialization in the broad archive described in (i) and (ii) above using state of the art observations developed in Project A1. This work will support Deliverable 2. **PDF02** with PK and JF in Years 3-4 will construct the appropriate sea ice perturbations and GCM integrations of CanAM4 based on the Hoerling et al. method and evaluate the utility of this method in CanAM4. **PHD01** with PK and JF in Years 1-4 will analyze the forced predictable component and its dynamics in both NCAR CAM4/CAM5 and the CanAM models (and additional integrations with LT and JS), and continue in Project C2.2. **PHD10** with SK in Years 1-5 will assemble sea ice datasets from CMIP5 simulations and develop model based empirical relationships between ice thicknesses and prior ice concentrations. **PHD07** working with JF, MS and SK in Years 1-5 will apply novel post-processing techniques in examining annual to decadal skill for predicting Arctic sea ice, snow and Atlantic meridional overturning and its high-latitude influences in CCCma and other CMIP5 model simulations. RB, CH, GF, BT and GB will aid in interpreting these results.

Project A4. Assessing limits to S/SI predictability (GB, SK, MS): Predictability studies estimate upper limits of skill ("potential predictability") to identify variables, regions and time scales for which useful predictions may be possible (Griffies and Bryan 1997, Boer 2000, 2004). This project builds on extensive research experience in the CanSISE team to determine the potential predictability of S/SI using coupled climate models. Robust conclusions require multiple models from the CHFP and CMIP5, as well as complementary estimation methods including the "diagnostic" analysis of variance methods (Boer 2000, 2004) and "prognostic" calculations of the rate of divergence of states (Griffies and Bryan 1997, Boer 2000). The project will begin i) with diagnostic analyses of S/SI variability in CMIP5 long-term simulations using methods developed previously for assessing diagnostic predictability of temperature and precipitation (Boer and Lambert 2008), partitioning this predictability into trend-dependent and trend-independent components (Boer 2010), and determining long-term changes in predictability in a warming climate (Boer 2009). It will continue by ii) applying the prognostic method to analyze S/SI predictability in seasonal and decadal forecasts (SK, GB). The initial perturbations in existing CCCma seasonal and decadal forecast ensembles will be used as a basis for assessing model-based prognostic predictability in S/SI on timescales up to a decade. The estimated predictive skill will be compared to the actual predictive skills determined in project A2. Finally, iii) the results will be extended to the methodology and focus of The Arctic Predictability and Prediction of Seasonal to Inter-annual Timescales (**APPOSITE**) project. APPOSITE seeks to quantify the predictability of the Arctic environment on seasonal to inter-annual time scales using the prognostic technique, with ensembles of simulations evolving from initially perturbed states. In this methodology, initial states are chosen specifically to sample minima and maxima of SIT, SIE, and Atlantic heat transport. This activity requires a limited set (<1000 years) of dedicated climate simulations to be undertaken which will comprise CCCma's contribution to APPOSITE.

EC-PDF04 working with WM will investigate 'perfect model' prognostic predictability for snow in CanSIPS hindcasts, whereas SK will perform comparable evaluations for sea ice and SK and GB will investigate diagnostic potential S/SI predictability in CMIP5 simulation, with all these potential skills being related to actual skills determined under A2. MS will produce and analyze the APPOSITE runs.

Section 2b. Area B: Attributing change in S/SI and modelling its impacts (Lead: FZ)

This research activity aims to identify the causes of observed S/SI changes, and determine their influence on impact-relevant variables. Building on previous detection and attribution studies on Arctic temperature change (Gillett et al, 2009), high latitude Northern precipitation (Min et al., 2008a), Arctic sea ice extent (Min et al., 2008b) and snow-storage and stream flow in the US Cascades (Barnett et al., 2008), we will attempt to attribute the causes of long-term S/SI and related changes in Canada and the Arctic. The projects outlined below fall into two groups. First, several studies (projects B1, B2 and B4a) are proposed to assess, update and augment studies of the causes of change in the climatic state that affects S/SI, and in key aspects of S/SI itself. These studies consider observed changes in temperature and precipitation (B1), SCE in the Northern hemisphere (B2), and Arctic SIE (B4a). They will use updated observations and will consider regional scales to the extent possible, including those needed to support the two case studies that are proposed in the second group of studies. The latter deal with two issues of critical importance to Canadians – the causes of the recent Arctic sea ice extent minimum (B4b), and the effects of changes in snow distribution on water resources as exemplified by changes in the Canadian Western Cordillera, including a key western drainage basin, the Fraser, which has important economic and ecological, as well as deep social and cultural value (B3).

These studies will provide a foundation for Deliverable 3, "Attribution of Cryospheric Events (ACRE)" discussed below. The studies will also provide strong links to both Areas A and C. The observational and process understanding developed in Area C will be critical, both for providing the observational basis for the attribution and impacts studies undertaken in Area B, and the physical basis for the interpretation of their results. Methods developed in Area A to study predictability of hydrologic impacts of snow-related variability on seasonal to subdecadal scales will be used here. In particular, the state-of-the-art statistical downscaling required to bridge the gap between the global scale climate models such as used in CanSIPS and the VIC hydrologic model will be developed jointly between Projects A2 and B3 and applied to both projects.

The work proposed for Area B is motivated by the urgency to understand the causes and impacts of the rapid changes that are taking place in S/SI and the cryosphere more broadly, as is evident from the extraordinary changes in Arctic SIE that are being observed and the continuing decline of snow cover. It is enabled by the availability of updated observational datasets that will be further augmented by Area C, a new cohort of comprehensive Earth System Models with substantially improved representation of S/SI processes, a mature and robustly supported hydrologic modelling capability, and world-leading expertise on downscaling techniques that are required to drive macro-scale hydrologic models.

Project B1: Drivers of S/SI change: High latitude temperature and precipitation: (NG, FZ, XZ, CD, SD): Prior to posing questions specifically related to the state of the snow and sea ice in Canada and the Arctic as a whole, an overarching question is whether human influence has affected high latitude temperature and precipitation in Canada and on a hemispheric scale. The identification and quantification of the anthropogenic contribution to changes in Arctic temperature and precipitation is likely to be of interest to stakeholders, while the information gleaned from such analysis on the relative sizes of the simulated and observed responses to individual forcings may help guide model development. Previous work using data and model simulations that end in 2009 for temperature and in 2000 for precipitation provide evidence for human influence in both fields at the hemispheric scale (Gillett et al, 2009; Min et al, 2008a). The objective of this project is to extend and update these studies, using newly available observational data and model simulations (CMIP5; Taylor et al, 2012) that extend to at least 2010, thereby including the most recent years in which ongoing rapid change has been observed in the Arctic climate system. To date only a combined anthropogenic influence has been identified in Arctic surface temperature. Using more spatially-complete observations coupled with more and better CMIP5 individual forcing simulations, we will attempt to separately detect and quantify the contributions of greenhouse gases, aerosols and natural forcing changes to Arctic temperature change. We will also evaluate whether this is now possible with precipitation, although the weaker signal-to-noise ratios in precipitation suggests this may still be difficult. Analysis of land surface temperature changes will use the newly-available Climatic Research Unit Temperature version 4 gridded observational dataset (**CRUTEM4**, Jones et al, 2012) which includes substantially enhanced coverage in the Arctic, including in Arctic Canada. Analysis of precipitation changes will use an updated version of the dataset developed by Zhang et al (2007) that is based on the Global Historical Climate Network (GHCN; Vose et al, 1992) and augmented with data from Canadian, Russian and other sources. The availability of simulations with both combined and individual forcings that extend into the 21st century will enable us to examine in detail how human influence has affected temperature and the distribution of precipitation on both regional (potentially including sub-regions within Canada that are small enough to contribute to Project B3) and hemispheric scales. The minimum anticipated analysis period for this study will be 1950-2010. Analyses for longer periods will also be attempted since, as has recently been demonstrated by Wan et al (2012), detection is likely to be enhanced over longer periods even if spatial coverage is reduced. The steps involved in conducting this study will include i) assembling the observational datasets required and acquiring the corresponding model output from the CMIP5 archive; this archive, which is rapidly maturing, contains a large suite of simulations of the historical instrumental era that are produced with multiple climate models, and that account for the effects of both natural and anthropogenic forcing agents combined, and those of subsets of individual forcing agents, such as natural forcing agents and greenhouse gases, thereby providing the information that will be required to attempt to separate the contributions from different forcing agents in observations; ii) the implementation of an enhanced detection and attribution formalism based on Ribes et al (2012a.b) that has the potential to substantially improve the estimation of the level of unforced (i.e., internal) variability in the diagnostics used to estimate long-term climate change; and iii) the application of this technique, as well as established (Hegerl and Zwiers, 2011) detection and attribution techniques to evaluate the extent of human influence on frozen and liquid precipitation and temperature, on scales ranging from hemispheric to regional and possibly large drainage basin scale (for use in B3).

PHD11 will be responsible for the detection and attribution analysis of high latitude temperature change. **U-PDF16** will undertake the detection and attribution analysis of high latitude precipitation. FZ and NG will provide overall guidance and supervision. XZ, CD and SD will assist with data gathering and evaluation, and the interpretation of results.

Project B2: Northern Hemisphere SCE (FZ, XZ, RB, SD, CD, NG): Snow cover plays a critical role in climate through its effects on surface albedo and modulation of land-atmosphere coupling. Subcontinental scale snow cover variations also have important hydrologic impacts, affecting spring flooding and available stores of soil moisture in the subsequent growing season. Observational evidence (Derksen and Brown, 2012; Brown and Goodison 1996; Déry and Brown 2007) shows that Northern Hemisphere SCE has declined over the 20th century and into the 21st century. It is therefore of primary interest to determine whether human influence on the climate has had a detectable effect on SCE. SCE has been well observed by satellite since 1967 (Robinson et al., 1993) and has been reliably reconstructed by Brown and Goodison (2006) and others for earlier periods – although with less spatial detail. Snow cover responds in a complex manner to both precipitation and temperature variability, with the latter dominating (Hamlet et al. 2005). Thus an appropriate strategy for determining whether there has been human influence on SCE is to first conduct a detection and attribution study on snow cover alone, and secondly, to consider snow cover and temperature simultaneously to determine whether consideration of both variables together provides stronger evidence for an anthropogenic influence on climate than consideration of either variable in isolation. The primary analysis period for this study will be 1967 to the present, which is the period for which high quality, generally homogenous remotely sensed snow cover data are available (Brown and Robinson, 2011). An attempt will also be made to conduct an analysis for a longer period using a combination of reconstructed observations (based on insitu snow observations) and remotely sensed data, but this latter study will only focus on regional SCE indicators. The steps involved in conducting this study will include i) gathering of observational and model data; ii) conducting a preliminary detection and attribution analysis of variations in decadally averaged seasonal mean SCE and in decadally averaged annual mean snow cover duration (**SCD**) using a standard detection and attribution formalism (Hegerl and Zwiers, 2011), including attempts to separately detect and quantify the contributions of greenhouse gases, aerosols and natural forcing changes to observed changes; iii) expand the analysis to account for the affects of temperature variation on SCE and SCD using a recently developed Bayesian technique (Ma, 2010); a preliminary analysis of North American SCE with this technique for winter and spring for the period ending in 2000 and using CMIP3 models strongly suggests that there has been a human influence on SCE during these seasons; iv) determine the robustness of the result to the choice of detection and attribution diagnostic (see also Project B1).

XZ, RB, CD, SD and **Res. Assist.** will prepare and assess the snow cover data. XZ and FZ will perform the detection and attribution analysis of changes in SCE. **PHD12** will extend this to SCD, and will evaluate the robustness of the detection results. All will contribute to the interpretation of results.

Project B3: Implications of precipitation and snow cover changes on water resources (SD, FZ, WH, NG): The Fraser River drains one quarter of BC and is its greatest river by annual discharge at over 100 km^3. As the most productive salmon river in the world, it is important for the economy and well-being of the region. Morrison et al. (2002) and Shrestha et al. (2012) project that climate change will drive a shift in the seasonality of the Fraser River so that it eventually transitions from a snowmelt- to a rainfall-dominated system by the end of the 21st century. Changes in air temperature and precipitation affect seasonal and longer-term storage in snow and glaciers, thus altering the timing and possibly the volume of Fraser River runoff. Observed streamflow phase shifts in the Fraser River and its tributaries between 1911 and 2010 will be assessed using a robust method developed by Déry et al. (2009). The causes of observed streamflow phase shifts will be established by investigating changes in the air temperature, precipitation and snow accumulation patterns and will take into account detection and attribution results from projects B1 and B2. This analysis will be based on VIC model simulations (Project A2.4) for the period 1953-2010 that will be validated with observed streamflow and SWE data. A downscaled version of the National Centers for Environmental Prediction (NCEP) reanalysis (Kalnay et al. 1996) based on Sheffield et al (2006; currently being updated to ¼° resolution), will be used to drive VIC. The driving data will be carefully validated against instrumental observations throughout the Fraser basin, and will be augmented with gridded instrumental precipitation data if required. VIC simulations will be validated with observed streamflow and SWE data, and sensitivity to the choice of driving data product will be investigated through the evaluation of results for shorter periods based on driving data from NCEP2 (Kanamitsu et al., 2002), European Centre for Medium Range Weather Forecasting Reanalysis “40” (**ERA**-40, Upalla et al, 2005), ERA-Interim (Dee et al 2011), and the high resolution North American Regional Reanalysis (**NARR**, Mesinger et al, 2006). Robustness to the choice of downscaling approach and resolution (Project A2.4; Buerger et al, 2012) will also be assessed. The changing contribution of snow accumulation to Fraser River runoff will then be established along with its sensitivity to air temperature and precipitation variations. These findings, together with results from projects B1 and B2, will enable a multistep attribution analysis (Hegerl et al., 2010) that will consider the extent to anthropogenic influences have played a role. We will also attempt a multi-variable detection and attribution analysis, similar to that of Barnett et al (2008), which will ask, in a one-step analysis (Hegerl et al, 2010) whether anthropogenic influence is detectable in temperature, SWE and the date of maximum annual streamflow combined, first in an ensemble of large western basins (the Columbia, Peace, Fraser and Skeena) and subsequently, specifically in the Fraser.

U-PDF06 will simulate Fraser River Basin historical streamflow, SWE and SCE using VIC and will assess the sensitivity to the choice driving reanalysis. **U-PDF07** will investigate the specific role of snow in the Fraser Basin hydrology. **U-PDF08** will investigate how downscaling uncertainty influences the determination of the causes of observed phase shifts in the basin, and **RA02** will be responsible for detection and attribution of regional hydrologic changes to anthropogenic forcing of the climate system. SD and FZ will provide supervision and all will contribute to interpretation and analysis.

Project B4: Causes of the 2007 and 2012 extreme Arctic SIE minima (NG, FZ, XZ, SH, GF, PK): The state of the ice cover of the Arctic Ocean is of crucial concern to Canada. Arctic SIE has been in decline since at least the early 1980's and achieved an unprecedented minimum in September of 2007 that was substantially exceeded in September 2012. Human influence on the climate system is understood to be one of the causes of the decline (e.g., Hegerl et al, 2007), and was established as a cause in a formal detection and attribution analysis by Min et al (2008b). It is often stated that individual climate events cannot be attributed to human influence. While this may not be the case for the events considered in event attribution studies to date, a finding that human influence had very substantially changed the likelihood of a given event, turning a previously rare event into a recurring outcome, would evidently contradict the statement. The objectives of this project are to first update the detection and attribution analysis of Min et al. (2008a), using updated observations and CMIP5 models. This will then provide a sound basis for our second objective, which is to estimate the effect of human influence on the likelihood of extreme Arctic sea ice extent minima such as those of 2007 and 2012, and to determine whether these events have been caused by human influence.

B4a) Detection and attribution analysis on Arctic SIE: The Min et al (2008b) analysis was based on the seasonal evolution of Arctic SIE extent for the period 1953-2006, and used CMIP3 simulated estimates of the expected response in Arctic SIE to natural and anthropogenic forcing. Our update of Min et al (2008b) will consider the Arctic in more detail by subdividing the Arctic basin into several sub-sectors, and will consider data up to 2012. Estimates of the response to forcing will be constructed from CMIP5, and as in Min et al (2008b), we will extend CMIP5 historical simulations to the present using emissions scenario driven simulations. As in projects B1 and B2, we will attempt to separately detect the response to greenhouse gases, aerosols and natural forcing. An important additional question that we will consider, if climate change simulations with suitable forcing are available, is whether there is evidence that deposition of black carbon has played a role in the observed reductions in Arctic SIE.

Our results will likely be sensitive to the choice of models from the CMIP5 archive, since models demonstrate considerable differences in their simulation of the historical evolution of Arctic SIE and the natural variability of Arctic SIE. Thus it will be necessary to make a careful choice of models from the CMIP5 archive based on the fidelity and complexity of the representation of Arctic sea ice, as well as the ocean and atmospheric circulation. Previous work has shown that simulated SIE trends (Boé et al., 2010) are sensitive to the simulated mean state in a model. We will examine the sensitivity of results to the exclusion of models with less realistic mean states, and will consider single model performance as well in support of project B4b.

B4b) Attribution of the causes of specific extreme SIE and snow cover events: Specific events, such as the extreme SIE minima of 2007 and 2012, or a potential extreme low snow cover event, can be studied using the fraction of attributable risk approach (FAR; Allen, 2003; Stott et al, 2004; Christidis et al, 2012) to estimate the change in probability of occurrence of such events due to anthropogenic influence. The FAR approach compares the probability of occurrence of an extreme event in an ensemble of simulations including anthropogenic forcing with that in an ensemble excluding this forcing. These estimates of the change of probability are strengthened by supporting detection and attribution results that demonstrate that human influence has contributed to long-term changes in related climate elements. For this study, that supporting evidence will be provided by projects B1, B2 and B4a. In order to reliably estimate probabilities, a key ingredient for a FAR analysis is the availability of relatively large ensembles of forced and unforced simulations with uniformly consistent properties. We therefore plan to construct two 50-member ensembles of CanESM simulations for the period 1956-2015:

one with natural and anthropogenic forcings and one with natural forcings only. Additionally, similar ensembles will be produced with NCAR CCSM and CESM1 on SciNet. Ensembles of this size, when coupled with statistical kernel estimation techniques, should be adequate to reliably estimate the probability distribution of SIE that should have prevailed, with or without anthropogenic forcing, since the beginning of the new millennium (i.e., during the period 2001-2015). The simulations that are planned will also be sufficiently long so that they can be used to calibrate simulated historical probability distributions against observed variability over the satellite era. Having evaluated model performance and obtained corresponding single model detection and attribution results, we will then perform the FAR analysis to estimate the extent to which human influence has affected the likelihood of occurrence of extreme minimum SIE events such as those of 2007 and 2012. These results will be underpinned by an analysis in Project C3.2 of the physical processes responsible for these record ice minima, including an analysis of meteorological and oceanographic conditions during the years concerned as well as preexisting ice conditions.

The approach described above can also be applied to other variables related to the distribution of seasonal snow cover. Northern Hemisphere spring snow cover extent has exhibited a significant downward trend,with successive record setting declines in recent years (Derksen and Brown, 2012). Using the same ensembles of simulations as those used for sea ice, we will examine the change in probability of extreme snow cover minima. Such an analysis should give us insight into whether the change in probability of extreme snow cover minima has indeed been less marked than the change in probability of extreme sea ice minima, or whether the risk has changed markedly, but this simply has not been strongly reflected in the observational record to date. If the latter is true, this might suggest that such events are more likely to occur in the future. This project would draw on an assessment of model biases in snow cover carried out in Area A.

Res. Assoc. 2 will perform the detection and attribution analysis of SIE and assist with the production and/or assembly of the model ensembles required for B4b with FZ, NG and PK. **EC-PDF03** will perform the event attribution analyses for sea-ice and SCE events with NG and FZ. **Res. Assoc. 2** and **EC-PDF03** will interact extensively at both CCCma and PCIC, which are both located on the Victoria campus. All will participate in the analysis and interpretation of results.

Section 2c. Area C: Snow and sea ice processes and climate interactions (Lead: JF)

This research activity encompasses analysis of GCM representation of S/SI processes and climate coupling. It is motivated strategically by the view that improved climate prediction requires improved process understanding. Its aim will be to examine a spectrum of interactions between S/SI and the climate system, as well as to examine simulated representation of S/SI processes. The proposed work leans heavily on the observational and modeling expertise assembled in this group.

The analysis will centre on the Canadian GCMs CanCM4 and CanESM2 with a view to providing useful information on their capabilities and extend to the larger set of CMIP5 decadal prediction and projection scenario integrations. In addition, selected sensitivity studies of models currently employed by members of the network, including the NCAR CESM, GFDL AM2 and AM3, UKMO HadGEM, and CNRM-GAME, will be employed. In coordination with Areas A and B, it will focus on those aspects of processes and teleconnected climate variability relevant to S/SI prediction and hydrological modelling.

We outline three projects that will be undertaken under Research Area C:

Project C1: S/SI related processes in observations and representations in Canadian GCMs: CanSISE will undertake a thorough analysis of S/SI processes that adversely affect predictive skill in the Canadian GCMs. Results of this will be summarized in diagnostic reports for the CCCma and EC (Deliverable 1). These diagnostics will be repeated as new versions of the model are released and guidance on improving these processes will be provided to the CCCma.

C1.1: Snow and sea ice albedo feedbacks and related impacts: S/SI albedo feedbacks (SAF) account for about 20% of the amplification of greenhouse forcing in climate change, display significant regional variation and involve a variety of S/SI processes (e.g. Fernandes et al. 2010, Perovich et al. 2007). The contribution of SAF to polar amplification of global warming is a topic of active research (e.g. Hall

2004, Serreze and Francis 2006, Screen and Simmonds 2010). Project C1.1 aims to evaluate simulated: i) snow albedo feedbacks and ii) sea ice albedo feedbacks, and provide guidance to the CCCma on how simulation of these critical processes might be improved.

C1.1-i: Snow albedo feedback (CF, PK, CD): Modeling uncertainty in snow albedo feedback contributes to inter-model variation in global climate sensitivity with consequences for regional responses to climate change (Hall 2004, Qu and Hall 2007, Fletcher et al. 2009 and 2012, Fernandes et al. 2010). SAF in the seasonal cycle, which can be evaluated observationally, provides a reasonable proxy for this feedback in climate change (Qu and Hall 2007). CMIP3 models have difficulty in representing the sensitivity of snow albedo to temperature, especially near the Canadian Arctic coast (Fletcher et al. 2012). Project C1.1-i will first update results of Fletcher et al. 2012 using recent observational and modelling products (MODIS satellite snow cover and albedo products, CanCM4, CanESM, and CMIP5 model output archive) to separately diagnose the temperature sensitivity of snow cover and snow albedo. Because these processes are highly uncertain in boreal forest regions, supplementary data from in situ BERMS flux towers in Saskatchewan, and 500 m resolved MODIS data up-scaled to GCM resolution, will be compared to CanCM4 and CanESM and offline calculations of the Canadian Land Surface Scheme (CLASS). Physical parameters related to uncertainty in snow aging, snow grain metamorphosis and black carbon deposition on the snowpack will be examined in the NCAR Community Earth System Model's (CESM1) Snow, Ice, and Aerosol Radiative (SNICAR) module. Snow microphysical parameters will be varied across their range of empirical uncertainty to determine their effect on SAF in response to doubled CO_2 conditions, and to identify areas for potential improvements in model physics. **PHD04** will analyze SAF in model simulations and satellite observational products, with a focus on northern boreal forest regions. **U-PDF09** will examine processes controlling SAF in a suite of offline land model simulations. **PHD05** will conduct the perturbed parameter simulations with NCAR CESM1.

C1.1-ii: Sea ice albedo feedback (CH, CD, PK, SH, JF, CF, GF, BT): Sea-ice albedo feedbacks are implicated in recent sea ice trends (Perovich et al. 2007), but the rapidity of Arctic sea ice loss events, influences from atmospheric surface winds (Project C1.2), and vertical coupling to the ocean (Project C1.3), make these feedbacks challenging to quantify from observations. Project C1.1-ii will evaluate the ability of models to simulate observed sea ice albedo feedbacks on a range of timescales. First, a decomposition of the seasonal feedback into parts related to temperature sensitivity of sea ice fraction and of sea ice albedo will be carried out for observations and models (analogous to Fletcher et al.'s 2012 analysis of snow albedo feedbacks). The observational analysis will use satellite derived sea ice concentration and albedo data from passive microwave, the APP-x, and MODIS products. Preliminary analyses may uncover serious issues in the feedback in the models that will inform Deliverable 1 at Workshop 1. A more detailed analysis will use sub-monthly data to more fully resolve surface-temperature sea ice coupling. For both C1.1-i and C1.1-ii, additional theoretical tools will be developed that relate regional albedo feedback factors to the planetary energy balance and help clarify the direction of coupling between temperature and S/SI. **U-PDF11** will evaluate the ability of models to simulate the observed sea ice albedo feedback in the seasonal cycle. **PHD02** with PK in Years 3-5 will further develop the theory of SAF and apply insights gained to the cases in this project.

C1.2: Changes of wind-driven ice drift and deformation in relation to ice thickness variations in observations and GCMs (CH, SH, JF, GF, CB, BT): The roles of underlying processes in driving the recent decline of Arctic sea ice are still unclear, i.e. the importance of thermodynamic and dynamic processes and their contributions to the thinning, removal of old ice, and changes in deformed ice thickness and volume. The prediction of the future fate of sea ice can only be performed reliably if a better understanding of these processes is achieved and implemented in models. The large-scale ice thickness distribution in the Arctic Ocean is primarily due to ice drift and deformation, with thickest ice occurring along the Canada and Greenland coasts as a result of convergent ice motion in response to the mean atmospheric circulation. Therefore, model and observational studies have shown that the Arctic sea ice mass balance is very sensitive to changes in atmospheric circulation (e.g. Holloway and Sou, 2002; Rigor et al., 2002). The velocity and direction of free ice drift and geostrophic wind are closely related (Thorndike and Colony, 1982), however, do strongly depend on ice thickness and roughness.

In this project we will analyze regional and temporal variations of the relationship between winds and ice drift based on observational, reanalysis, and model data. We will investigate if any changes in the response of ice drift to winds have occurred and where, and how these are related to changes in ice thickness and ridging intensity. The work will strongly rely on improved sea ice data sets compiled in Subproject A1. Based on these findings and the results of validations of ice drift and thickness in Canadian GCMs we will perform model sensitivity studies, e.g. as in Bitz et al. (2002), by varying wind forcing and wind-ice coupling parameterizations to see if better agreement with observation-based estimates can be achieved. This project will primarily contribute to Deliverable 2. **U-PDF11** will examine wind-driven ice drift and deformation processes using high-resolution, satellite derived ice drift products; **PHD08** will assess long-term variability of wind-ice coupling based on data, relate this to ice morphology and thickness changes, compare the results to wind-ice coupling in models, and suggest improvements.

C1.3: Towards improved sea ice physics and dynamics in the Canadian GCMs (BT, JF, GF, WM): In this project we will investigate a known low bias in minimum sea-ice (September) extent and thickness in CanESM2 (Stroeve et al. 2012). The dynamical component of the sea-ice model in CanESM2 is based on cavitating fluid rheology (Flato and Hibler, 1992), with sea ice behaving as a plastic material in compression with no resistance to shear motion. This leads to faster sea ice drift for a given surface wind stress forcing, higher ice export and reduced sea ice thickness, compared with a fully viscous plastic sea ice model including resistance in shear and compression (e.g. Liu et al, 2003).

In this project we will couple a new sea-ice dynamic model with an efficient solver for the solution of the highly non-linear sea ice momentum equation (Lemieux et al. 2008, 2010). Operating much faster than other commonly used schemes, the new solver will be implemented in the CICE sea-ice model developed at the Los Alamos National Laboratory (and used, for example, in the NCAR Community Climate System Model). The Newton's method that underlies the solver allows for full convergence of the momentum equation and good representation of Linear Kinematic Features (or leads, LKFs) at reasonable cost (Lemieux and Tremblay 2009). The sharp gradients in sea ice drift across narrow leads impose large gradients in the surface ice-ocean stresses, leading to Ekman pumping and potentially large vertical ocean heat fluxes (e.g. McPhee et al, 2005). Different sea-ice rheologies with different yield curve represent LKF pattern in better agreement with satellite observations when compared with the standard elliptical yield curve. These rheologies, developed under separate funding, will be tested and considered in CanESM2 as they become available. Vertical ocean heat fluxes and vertical ocean structures simulated by the CCCma GCMs with improved sea ice physics and numerics will be compared with observations (e.g. North Pole Station, SHEBA). Finally, new brine parameterizations (e.g. Nguyen et al. 2009) leading to a more realistic cold halocline layer will be considered, and the effect on the vertical ocean heat fluxes on simulated ice thickness and extent biases quantified. This project will primarily relate to Deliverable 1 (model evaluation). **U-PDF13, 14, and** 15 with BT will be responsible for the evaluation of new sea ice components in CanESM2, the characterization of the vertical ocean heat flux and temperature/salinity structures, and the comparison of CanESM2 ice/ocean properties with in-situ observations. GF, JF, and WM will provide advice on possible implementation of new sea ice modules in CanESM2.

Project C2: Connecting S/SI to the large-scale general circulation: CanSISE will undertake an analysis of S/SI processes that impact mid-latitude circulation and storm tracks, as well as an analysis of those lower latitude processes that impact S/SI variability and change. These projects will primarily contribute to Deliverables 1 and 2.

C2.1: Changes in SIE and impacts on mid and high latitude circulation (JF, BT, MS, PK, CF, WM, JS, SS): A reduction of SIE causes an increase in moisture and turbulent heat flux from the ocean to the atmosphere, which can affect larger scale atmospheric circulation, storm tracks, the strength and frequency of blocking events, and precipitation patterns. Increased surface heat flux and surface temperatures due to sea ice loss can also act to decrease the baroclinicity of the atmosphere by reducing the meridional temperature gradient. This, in turn, can alter the frequency, intensity and location of storm tracks in the mid and high latitudes. All of these factors may influence precipitation.

In this project, we will investigate the climate response to Arctic sea ice loss by performing sensitivity experiments with CanCM4 and its atmosphere-only counterpart CanAM4. Specifically, we will investigate which aspects of the coupled climate system responding to increasing greenhouse gases can be directly attributed to Arctic sea ice loss, and which aspects are due to other processes like increased radiative forcing. Following Deser et al. (2010), we will compare the climate response to increasing greenhouse gases as simulated by the coupled model (CanCM4), with the climate response resulting from the sea-ice loss by specifying CanCM4's sea ice as boundary condition to the atmospheric model CanAM4. Similar experiments will be carried out in the near future with the stratosphere-resolving version of the previous generation CCCma model (CMAM, which is based on CanAM3) as part of an international collaborative project led by Dr. Clara Deser at NCAR. By repeating such experiments with CanCM4/CanAM4, the robustness of the Arctic sea ice loss impacts can be assessed employing the latest versions of CCCma climate model. Sensitivity experiments with perturbed boundary conditions in CanCM4/CanAM4 will be compared to similar experiments with the atmospheric component of HadGEM(2/3) (undertaken by JS). **EC-PDF02** with JF and MS will be responsible for preparing and executing the sensitivity experiments with CanCM4, and its atmosphere-only counterpart CanAM4. The experimental design will be developed in consultation with other University-based and international collaborators (PK, BT, CF, JS, SS), and the output from the experiments made available to them to undertake joint analyses. Results from Project C2.1 will contribute to Projects A2.1 and Deliverables 1, 2, and 3.

C2.2: S/SI response to teleconnected forcing (PK, JF, CF, JS): High latitude climate is remotely influenced by oceanic circulation, atmospheric teleconnections and transport of heat, momentum, and moisture from extratropical cyclones, etc. (e.g. Serreze and Barrett 2008, 2011; Screen et al. 2012). This project seeks to quantify the extent to which long-term variability and projected changes to S/SI and Arctic climate are remotely forced, focusing on atmospheric pathways. Trends in extratropical regional climate have been found to be strongly influenced by the spatial structure of sea surface temperature (SST) trends in the tropical oceans (Shin and Sardeshmukh 2010; Hoerling et al. 2011). An open question is the extent to which such tropical influence extends to seasonal S/SI variability and trends, and more generally which regions most efficiently force S/SI and Arctic climate. Addressing this question will provide guidance on how improvements to lower latitude simulations might be expected to improve S/SI and Arctic simulation and climate prediction. For seasonal snow cover over the continental regions, such questions are readily addressed in an AGCM with SSTs prescribed in the tropics, subtropics, and lower extratropics. We propose to carry out simulations imposing observed SST trend patterns, as well as future projected SST patterns, to examine the impact of such trends on seasonal snow cover. The method for generating the SST patterns will be similar to that used in Project A3 for determining the radiatively forced predictable signal of regional snow cover. As in A3, identical perturbation set ups for NCAR CAM4/CAM5 and CanAM4 will be employed. Time slice integrations will be carried out with SSTs prescribed over different regions and the teleconnected response into Northern high latitudes and the Arctic will be examined. Particular attention will be paid to factors influencing snow distribution in the subarctic and boreal regions, and in the Western Cordillera. The recent trends in snow pack and runoff in the Western Cordillera, described in Project C1.1, may well be strongly influenced by tropical Pacific and North Pacific SST trends, and a dedicated diagnostic focus on this issue will be undertaken. For seasonally varying sea ice, we will employ a different simulation set up in which a mixed layer ocean coupled to a sea ice model will be used in regions where SST information is not prescribed (as in Alexander et al. 2002; Jin and Kirtman 2010). These simulations will be carried out for both the Canadian and NCAR GCMs, as well as with HadGEM2 as they become available (undertaken by JS). **PHD01**, co-supervised by PK and JF in Years 1-4 will carry out time slice integrations for SST perturbations in selected regions. **RA01** with PK and JF in Years 3-5 will develop, implement, and analyze the results of the mixed layer ocean methodology for CAM4/CAM5 and, if feasible, will work with JF to implement it in CanAM4.

Project C3: Analysis of variability and trends of S/SI: Recent analyses of the satellite data record (1967-2012) have identified significant reductions in spring season SCE across the Northern Hemisphere, with changes since 2008 occurring faster than predicted by CMIP5 models (Brown and Robinson, 2011; Derksen and Brown, 2012). As well, over the passive microwave satellite record (1979-present) Arctic sea ice cover is experiencing declines in all months of year with the largest (~12% per decade) occurring in September (Stroeve et al., 2011), and CMIP5 models predict that a summertime sea ice-free state will likely be reached between 2030 and 2045 (Stroeve et al., 2012). This project will be focused on understanding these changes, and will primarily relate to Deliverables 2 and 4.

C3.1: Declining SCE: Characteristics and causes (CD, RB, SD): An analysis of the 1972-2006 trends in Northern Hemisphere SCE reveals marked declines due in part to the snow-albedo feedback (Déry and Brown 2007). This project will provide an update on previous analyses of SCE trends to include data from 2007 to 2013 from the Rutgers University Global Snow Lab (this time series is also used in Project B2). Emphasis will be given to the role of elevation on observed trends as observations show enhanced declines in snow cover duration in the North American Cordillera (Déry and Brown 2007) that are consistent with climate model projections (Fyfe and Flato 1999). We will then explore the role of the snow-albedo feedback on other climatic variables such as air temperature and precipitation phase (Scherrer et al. in press). Attention will also be given to understanding the drivers of change by using ancillary data (e.g., air temperature, precipitation, SWE and snow depth, teleconnection indices, and sea ice) and we will explore feedbacks with S/SI in the Arctic and our other regions of interest. Observations indicate a seasonal asymmetry in changes to SCE, with significant reductions in the spring period but comparatively little change during the snow cover onset period, in spite of a significant surface temperature warming signal in both seasons. This is consistent with a lower sensitivity to observed temperature in the snow onset period compared to the spring melt period. The extent to which this seasonal difference is captured in CMIP5 simulations will also be explored. The **Res. Assist.** will prepare and assess trends in snow cover data, and assisted by CD, RB, SD, will analyze relationships between SCE and topography, climate conditions, and teleconnection indices and feedbacks. The **Res. Assist.** will also investigate the seasonal asymmetry in snow cover trends.

C3.2: Declining Arctic SIE: This project will focus on two themes related to future sea ice variability and change: i) the use of satellite observations and model simulations to gain an improved understanding of the remnant multi-year ice (MYI) when the remainder of the Arctic Ocean is sea ice-free and ii) assessing the capabilities of models to simulate the new regime of first-year ice (FYI) across the Arctic Ocean. **U-PDF12** will contribute to the analysis of changes of sea ice albedo and deformation using the newly compiled data sets from project A1. This work will contribute to the analysis of variability in predictions (A3).

C3.2-i: Changes in sea ice area and type in the Canadian Arctic Archipelago (CD, SH, CH): Model simulations indicate sea ice to be present within the Canadian Arctic Archipelago (CAA) when the Arctic Ocean is sea ice-free during the summer months (e.g. Sou and Flato, 2009) but little attention has been directed toward evaluating model performance in this region. Observational evidence indicates that a warming climate may very well increase the presence of MYI in the CAA (Howell et al., 2009). The islands interspersed among the waterways of the CAA complicate model projections, particularly during the winter to spring transition, such that even as model resolution increases, problems with the CAA will still remain (Howell et al., 2008). The objective of this project is to assess CMIP5 performance in the remaining 1 million km^2 sea ice region located primarily in the CAA. Understanding changing future sea ice conditions in this region is of particular importance for Northwest Passage shipping. We will select sea ice simulations in the CMIP5 model archive and evaluate their performance relative to observations from the CISDA (Tivy et al., 2011). Thermodynamic state estimates will be derived from passive microwave retrievals (Markus et al., 2009) and regional ice dynamics will be produced from RADARSAT (Wohlleben et al., in press). This analysis will help resolve the interplay between sea ice dynamics and thermodynamics within the CAA (when most of the Arctic Ocean is ice free) and identify climate model capabilities in this important region.

C3.2-ii: Changes in pan-Arctic SIE, thickness and snow on ice (CD, SH, CH): As the majority of Arctic Ocean sea ice transitions from a MYI to a FYI regime the response to atmospheric and oceanic forcing will undoubtedly change. This project will focus on the application of new observational datasets to provide information on the characteristics of FYI and apply these datasets to the evaluation of 21st century CMIP5 predictions. The focus will be on two key observational parameters: sea ice thickness and snow on sea ice. Ice thickness observations will be produced from radar altimeter measurements from Cryosat-2 (Kwok et al., 2009). Snow on MYI has always represented a significant observational challenge, but passive microwave retrieval algorithms are available for first-year ice (e.g. Cavalieri et al. 2012), while the ongoing NASA IceBridge campaign is providing significant new observations from suborbital platforms (e.g. Kwok et al. 2011). New ice thickness and snow on sea ice datasets will be evaluated using Arctic airborne observations of CH. These datasets will also be utilized within project C1.2. Observed ice thickness, snow on sea ice, and SIE data records will then be utilized to evaluate CMIP5 projections of seasonal sea ice characteristics during the winter season. Model biases in variables such as ice area will be diagnosed through an assessment of ice thickness and snow on sea ice. Finally, the physical processes responsible for the record ice minima in 2007 and 2012 will be investigated in support of Project B4 and Deliverable 3.

Section 3. DELIVERABLES

The Research Area projects involve intensive scientific focus and have basic research and applied aims. The following *Deliverables* are intended to synthesize the results of the Research Area science, coordinate research across the Network, and provide concrete outcomes of value to our partners and their aims, including EC's planning and policy work, PCIC's impacts assessments for the Western Cordillera, and CIS's operational sea ice prediction systems.

Deliverable 1. Assessment of S/SI Biases, Projections, and Predictions in the Canadian GCMs (PK, and most of CanSISE membership) This Deliverable is an outcome of Areas A and C. The principal objectives of Deliverable 1 are i) to provide an overall assessment of the quality of simulation of climatological S/SI and their coupling to climate variability in the Canadian GCMs, ii) to assess the prediction skill of the GCMs in hindcast mode and its ability to reproduce observed S/SI and related climate variability, and iii) to determine the physical underpinnings and directions for improvement for unrealistic features of the GCMs. This Deliverable has an initial milestone of providing a diagnostic assessment early in the CanSISE Network that will be repeated as new model versions are released, and a final milestone of providing a review of progress in simulating S/SI processes at the end of the Network. The diagnostic report will be compiled in a graphical and tabular format that will be easy to expand upon over the lifetime of the network and repeated on a routine basis for new model versions. Deliverable 1 will highlight simulated biases in the oceans, sea ice, and land surface that might lead to climate drift and thus adversely affect prediction skill of integrations initialized with realistic ocean and sea ice data.

The first thrust of this activity is a detailed analysis of the CanCM4 and CanESM simulations that have been prepared for CMIP5. Results from these will be summarized and compared across the suite of CMIP5 integrations. A report on this first effort --- the "CanSISE Workshop 1 Report" --- will be prepared by the Toronto group and be the focus of the first CanSISE workshop at the CCCma in Victoria. Along with CanSISE Network members, CCCma modellers will be invited to engage in this workshop. The baseline diagnostic set developed for the CanSISE Workshop 1 Report will be applied to newer versions of the CanCM and CanESM in development, thus documenting the evolution of the models' S/SI and cold climates simulation over time. This documentation will help enable a strategic focus on critical areas of simulation improvement in collaboration with CanSISE's observational researchers. For example, early indications are that SIE and thickness are biased low in CanESM2. The latter can be formally assessed using new ice thickness measurements described in Project A4 and will be updated as new versions of the model become available. Estimates of SAF components and hydroclimatological parameters in the Western Cordillera will also provide more stringent tests of model performance over the lifetime of the network.

The second thrust of this Deliverable will be an assessment of prediction skill for S/SI, as well as of historic and projected S/SI trends will be assessed. For example, in response to greenhouse warming, this class of GCMs typically produce an increase in annual maximum SWE over high latitudes. This has not been detected in observations despite evidence of increasing precipitation. Using the results of Research Areas A and C, an assessment of those aspects of seasonal to multiannual prediction derived from initialization and external forcing will be carried out for several S/SI and related variables. This assessment will, as for the simulation-quality analysis above, be repeated as new versions of the model become available, because it is expected that both signals will be highly model dependent.

A final update on this deliverable will form part of the CanSISE Workshop 3 Report. This update will review progress in simulation and prediction of S/SI that has occurred over the lifetime of the CanSISE Network.

Deliverable 2: Assessment of Canadian Snow and Sea Ice for the next decade (CD, PK, RB, JF, GF, SS, GB, CB, CH): Studies undertaken during the International Polar Year (IPY, 2007-8) enabled a comprehensive observation-based assessment of the state of the Canadian cryosphere in that epoch in relation to mean conditions and variability across preceding decades. The overall message of that assessment was that the Canadian cryosphere is on a trajectory of rapid and accelerating change that exceeds the bounds of recorded variability (Derksen 2012). The objective of Deliverable 2 is to interpret this observational assessment in the context of climate variability and change as simulated by the CCCma and other CMIP5 climate models. We choose to focus on S/SI processes in this deliverable to reflect the strengths of the modelling tools we use and our expertise. This Deliverable will evaluate modeled changes in S/SI through the present day and into the next decade in order to provide a new assessment for likely future changes on this horizon. Input for the assessment will come from

1. Enhanced observational time series developed under Area A project A4, which will enable observed changes since IPY to be assessed while providing a consistency check with IPY-derived results to ensure that any offsets or biases between the corresponding data collections are accounted for;
2. Evaluations of existing CMIP5 short-term decadal predictions and long-term climate simulations conducted under Area A project A3, adjusted for biases in climatic means and trends as evaluated using the enhanced datasets from project A1;
3. Analyses from Area C of S/SI processes and their coupling to the atmosphere, land surface, and ocean; these will be used as a framework for interpreting causes and effects in the context of the observed and modeled trends and variations.

Deliverable 2 will be produced in the 3rd year of the network and timed to coincide with the second network workshop in the February 2016. Its results will be reported in the context of the IPCC 5th Assessment, which will have been published near the end of the 5th Assessment cycle in 2013-2014, and outcomes of the BREA which concludes in 2015.

Deliverable 3: ACRE – Attribution of Cryospheric Events (NG, FZ, SD, XZ, PK, CD, RB)
The rapid change that is taking place in the Arctic imposes upon Canada a need to adapt its Arctic policies, which in turn imposes an urgent need to better understand historical change and its causes in the Arctic S/SI, in the broad context of cryospheric change. The studies undertaken in Area B will contribute significantly towards this goal, and will provide insights that will enable further development of the science. This deliverable is intended to inform policymakers and other users of the insights that are gained from Area B studies. The modes of delivery include a network workshop in February 2016 which will present key results on human induced change in the S/SI, and discuss their application with relevant stakeholders such the Canadian Ice Service, Indian and Northern Affairs Canada, Natural Resources Canada and BC Hydro. This workshop will focus on the causes of observed changes in the S/SI, including the attribution of specific extreme events in S/SI, and will also include assessment of the implications of the changes in the distribution of seasonal snow cover for extreme hydrologic events in the Canadian Western Cordillera. This workshop will familiarize the academic, government and other

user communities with results of the project, facilitate further analysis in collaboration with these communities, and provide guidance for completion of Area B research. Further modes of delivery will include the transfer of associated scientific methodologies and their implementation to users in EC, PCIC and elsewhere, and peer-reviewed publication of methodologies and findings.

A key approach will be the application of Attribution of Climate Events techniques (ACE; Stott et al. 2004) to S/SI — a proposed methodology we call *Attribution of Cryospheric Events* or "ACRE". ACRE is intended to determine whether and how much anthropogenic influence contributed to the probability of occurrence of specific observed extreme events. A new approach for ACE will be developed and applied to the attribution of extreme S/SI events. Previously such approaches have primarily considered the attribution of meteorological events, and not those associated with the coupled atmosphere-ocean-ice system. Results will include an estimate of the anthropogenic contribution to the probability of extreme minima in sea ice such as those observed in 2007 and 2012, and an assessment of whether these minima might be directly attributed to anthropogenic influence. These results will be underpinned by an analysis of the physical processes responsible for these record ice minima, including an analysis of meteorological and oceanographic conditions during the years concerned as well as pre-existing ice conditions (Section 3.2). There will also be assessments of the anthropogenic contribution to extremes in Northern Hemisphere SCE and the implications of the change in snow distribution for peak flows in river basins in the Canadian western cordillera. Assessment of the anthropogenic contribution to high latitude mean state changes in sea ice, temperature, SCE, and precipitation will also be included. Where possible, results of regional attribution analyses over Canada will be presented.

Deliverable 3 links well with the CCAR themes and with GoC science priorities. According to the EC Science Plan, EC's science objectives include understanding past and present trends and future projections of environmental change, as well as the application of such environmental predictions to risk-management, adaptation, and mitigation. EC's Climate Research Division priorities include a focus on climate change detection and attribution studies, including characterization of climate extremes and variability. Quantified estimates of the human contribution to S/SI extremes and trends, as well as changes in related variables will directly contribute to furthering these objectives. Outputs from this project will also assist EC in its contribution to the IPCC process, including the scoping of a possible IPCC Sixth Assessment Report.

Deliverable 4: Observations to improve S/SI prediction

This Deliverable is an outcome of Areas A and C, and will result in a report to EC that will present:

1. Key S/SI observables required to improve model biases and increase prediction skill identified in Deliverable 1, and required accuracy and temporal and spatial coverage of these observables.
2. Recommendations for optimized observation systems to improve seasonal to decadal S/SI prediction.
3. Emerging remote sensing and in situ observational opportunities that could address climate modeling applications including the identification (and correction) of processes that limit model performance.

This Deliverable will identify the key observables required to better constrain model initialization in climate prediction as well as to help improve model biases. It will include a summary of the accuracy and spatio-temporal sampling requirements of S/SI parameters such as SIT, SWE, etc.. Near the end of the network, model sensitivity studies will be proposed to perform an Observation System Simulation Experiment (OSSE) for S/SI variables, a methodology we call "Cryospheric-OSSE" (C-OSSE). An initial C-OSSE analysis developed by CanSISE will contribute to recommendations for an optimal and cost-effective future Northern Hemisphere observation system to support climate monitoring and seasonal to decadal prediction. In other settings, OSSEs have been performed in preparation of the design of global atmospheric observation systems (e.g. Masutani et al., 2010).

The experiences of the CanSISE project will be used to inform emerging observational S/SI programs in other ways. We will estimate the impact on reducing uncertainty in S/SI observations of new remote sensing observations, including the new NASA VIIRS and ESA Sentinel-2 and Proba-V platforms, and potentially the first ever geostationary-type observations over high latitudes (the proposed Polar Communications and Weather mission). Synthesizing Projects A1 and C3.1 with comparisons with other satellite derived SCE datasets (e.g. GlobSnow SCE) and reanalysis products will further inform our understanding of SCE observational capability. We will determine the extent to which uncertainty in current SWE datasets (25 km resolution) limits our ability to both initialize and meaningfully validate climate model simulations. Satellite radar measurements at X- and Ku-band (as proposed by the ESA Earth Explorer-7 CoReH20 mission) could produce the first high resolution (~200 m resolution) SWE retrievals, but the orbital and swath characteristics do not provide complete spatial coverage, even at high latitudes. The creation of datasets suitable for climate model evaluation from the high resolution but spatially discontinuous retrievals provided by missions like CoReH20 will also be explored. Finally, the role of IceSAT-2 Lidar measurements in producing high resolution snow depth retrievals must also be determined.

As part of our Deliverable 4 report, CanSISE will gauge the potential to improve process understanding and prediction of new satellite sea ice retrievals (e.g. concentration, stage of development, thickness, and motion). First, satellite C-band radar data are available from constellations of e.g. RADARSAT and ENVISAT, significantly increasing the temporal coverage of the Arctic without sacrificing spatial resolution. We will assess whether retrieval techniques under development for future satellite missions like Sentinel and the RADARSAT Constellation Mission (RCM) might improve our ability to evaluate simulated ice feedbacks and dynamics (Project C1.1 and C1.2). Second, satellite based altimetry measurements (laser altimetry from ICESat and ICESAT-2; radar altimetry from Cryosat-2) will provide new opportunities to investigate snow on sea ice and ice thickness. We will also assess whether this data, if coupled with ice motion estimates, altimetric datasets might permit calculation of regional ice volume budgets for comparison with model simulations. Third, the increased availability of multi-polarization sensors (e.g. RADARSAT-2, TerraSAR) and satellite radar measurements at L-band (e.g. PALSAR-2) reduces ambiguity in the sea ice surface state during the melt season. These new sensors will improve ice concentration and stage of development retrievals and therefore provide improved information for improvement of model parameterizations. This will raise the possibility of developing sea ice modelling development plans around the newest available observations.

Besides the report to EC and other Canadian stakeholders, Deliverable 4 will contribute to national and international efforts to improve observational capabilities and networks. CanSISE will synthesize the results of Projects A1 and A2, which will develop new observational datasets for seasonal prediction and then determine their impact on prediction skill, and use them to provide into the S/SI observational plans of the GCW, the WMO polar prediction program, and the AMAP. In parallel, airborne observational capabilities (2D Lidar altimetry, EM ice thickness sounding, radar snow thickness surveying) are improving in accuracy and spatial coverage, and efforts for an international Pan-Arctic observational network have been initiated by the US Study of Environmental Change in the Arctic (SEARCH) Arctic Observing Network (AON) Program. Insights derived from CanSISE could contribute to the design of these new observational networks.

Section 4. RESEARCH TEAM EXPERTISE INTEGRATION; KNOWLEDGE TRANSFER

Section 4a. Research team integration

CanSISE assembles Canada's leading expertise in S/SI processes, climate dynamics, climate modelling, and observational analysis, and connects with partners in key sectors in which climate information is critical. The Network is lead by PK, one of Canada's foremost theoretical climate dynamicists whose formative team leading experience was to co-lead the NOAA GFDL Global Atmospheric Model Development Team in construction of the GFDL AM2 atmosphere/land GCM. PK has committed to overall coordination of the Network, leadership in specific projects in Areas A and C, and leadership on Deliverable 1 in Year 1 of CanSISE. Similarly, each of the Research Area leads (WM, FZ, JF) has extensive collaborative team experience and bring to bear a track record of modelling expertise and excellent scholarship to their respective Areas.

Area A will integrate expertise in climate and hydrological modelling, prediction, and analysis together with S/SI observation to advance prediction of Canadian S/SI and their impacts on time scales ranging from a month to several decades. The Area A research team assembles the necessary breadth and expertise to meet this challenge. Observationally, CD and CH bring to Project A1 strong expertise in surface-validated remote sensing of terrestrial snow and sea ice properties respectively, and in interpreting these measurements in the context of S/SI variability and change. Complementary expertise comes from SB who is lead developer of EC's CaLDAS, which synthesizes a global view of land surface properties and evolution. WM is lead developer of CanSIPS, which underlies all A2 subprojects and will itself benefit from these activities. SK and MS bring to A2.1 considerable prior expertise in analyzing CanSIPS output, which will inform and be informed by the experience of SH, RB, CD and CH in analyzing observed S/SI variations. AB brings to A2.2 considerable experience in analyzing land data products and seasonal forecasts initialized with observational land fields. GF leads and is the primary expert on sea ice modelling at CCCma. The A2.4 streamflow prediction studies will be led by experts on high-latitude and alpine hydrometeorology (SD), climate analysis (FZ, who heads PCIC) and the nonlinear machine learning methods that will be applied to the complicated interrelations between SWE measurements, satellite data and model forecasts (WH). Project A3 will draw on strong expertise in analyzing modelled future changes in circulation (PK, JF), sea ice (BT) and snow (RB), whereas GB is a leading expert on and developer of the predictability analysis techniques that will be applied in A4.

Area B will integrate expertise in climate change detection and attribution with expertise in S/SI and climate observations, and hydrologic and climate modelling to advance our understanding of the causes of observed changes in Northern Hemisphere S/SI and in the role of seasonal snow cover in the hydrology of the Canadian Western Cordillera. Area B also integrates expertise from multiple institutions in the university community with expertise that represents the breadth of the Climate Research Division of EC, thereby facilitating knowledge and technology transfer. All Area B projects have important detection and attribution (D&A) components to determine the causes of observed changes. D&A activities will involve all levels of HQP, providing extensive training opportunities, and will be lead by world leading experts on detection and attribution (NG, FZ, XZ, all of whom serve, or have served, as IPCC lead or coordinating lead authors on this topic). Observational expertise specific to snow cover (RB, CD, SD), sea ice (SH) and precipitation (XZ, CD, SD) will be involved at all stages of the research to ensure that our analysis is based on the best available observations, and that our analyses and interpretations are properly constrained by observational limitations. Further, we will link with Area C projects to ensure consistency with physically based process understanding, and project A2.4 to integrate CanSISE statistical downscaling developments into Area B research. In addition, Project B3 will integrate hydrologic modelling expertise at UNBC (SD is a leading expert), UBC (WH) and PCIC with climate change detection and attribution expertise at PCIC and CCCma. All Area B HQP will be involved in multi-institution, multi-disciplinary collaborations, typically involving modelling, observational, and statistical analysis. Most HQP will be jointly supervised by two Area B investigators.

Area C brings together the observational and modelling expertise required to advance our understanding of the key S/SI processes and feedbacks underlying Arctic variability change, and their potential impacts on mid-latitude circulation. On the observational side, CD, CH, SH, SF and RB bring world-class expertise in remote sensing of snow and sea ice properties, and in interpreting those measurements in the context of S/SI variability and change. This observational expertise will be exploited across all activities of Area C, i.e., in C1.1 (S/SI feedbacks), C1.2 (ice drift/deformation and sea ice thickness), C1.3 (sea ice physics), C2.1 (S/SI impacts on storm tracks), C2.2 (S/SI response to circulation), and C3 (S/SI variability and trends). On the modelling side, Area C will draw upon recognized experts in the development and evaluation of global climate models (PK, JF, GF, WM, MS-noting that JF served as IPCC lead author, and serves as review editor, on this topic), as well as on top experts in the S/SI relevant subcomponents of those models (e.g. BT and GF for sea ice; CF for snow processes; CD for hydrological processes). Together this team is well aligned with the overall objectives of the CanSISE Network, an in particular with the Area C objective of improved S/SI prediction through enhanced process understanding.

Section 4b. Interaction with partners and international collaborators

The CanSISE Network is partnered with the Atmospheric Science and Technology Directorate (ASTD) and the Meteorological Service of Canada (MSC), both of Environment Canada (EC), and with the Pacific Climate Impacts Consortium (PCIC). Scientists from each of these partnering organizations will be full participants in the network contributing to all facets of its work, including the innovation that will be required to meet research objectives. Representing the ASTD to the CanSISE Network are co-applicants and steering committee members: JF, WM and CD. Aside from supervising and co-supervising HQP across all three research areas of the CanSISE Network, these ASTD researchers (together with NG) will provide expert advice and support staff, as appropriate, to help initiate and conduct sensitivity experiments using the suite of Canadian climate models, and will guarantee that the output from those experiments, and their validating observational datasets, are made available to their university collaborators in a timely fashion. As head of "Application and Analysis" activities at the ASTD/CCCma, JF will engage all GoC scientists and university and PCIC partners, as appropriate, in regular CCCma meetings where new experiments are designed, initiated and disseminated. Observational expertise from the ASTD (RB, CD, SH, XZ) is fully integrated across all the research areas of the CanSISE Network. Representing the MSC are collaborators SB and partner Tom Carrieres (from the Canadian Ice Service). Representing PCIC within the CanSISE Network as co-applicant and steering committee member is FZ (also PCIC Director). The full extent of the interactions between the CanSISE Network and partners has been made clear in the proposal and in the letters of support from the ASTD, PCIC, and the Canadian Ice Service. The international collaborators (JS, LT and SS) and advisory panel members (CB, DL, TM, DP, DS) were carefully selected on the basis of their track records in successfully collaborating with CanSISE Network researchers, and are they fully integrated into its work plans where appropriate. In every way, the CanSISE Network has been designed to ensure maximal integration and involvement of all its partners, as well as its international collaborators and advisory committee members. Finally, further indicating international engagement of our researchers, CanSISE has been asked to form links with two other international proposals: i) A U.S. proposal entitled *An innovative network to improve sea ice prediction in a changing Arctic* with CB, W. Wang, J. Stroeve, and others, and ii) a Norwegian proposal entitled *Role of sea ice on variability and predictability of Arctic and Northern Hemisphere* with Keenleyside, Wettstein, and others.

Section 4c. Plans for knowledge transfer to federal departments and other potential end users

The GoC component of the CanSISE Network involves 4 co-applicants (JF, WM, NG and CD) and 7 collaborators (GF, GB, SB, RB, SK, SH and XZ) whose responsibility it will be, led by GF (as CCCma manager), to ensure the transfer of knowledge and technology to the GoC later in the life of the CanSISE Network. Other points of knowledge transfer will occur through the schedule of workshops and specialized reports (as indicated in the proposal). The workshops, in particular, will have as invited participants many GoC scientists and managers (e.g. from EC and MSC) and potential end users (e.g. from PCIC and the Canadian Ice Service).

Section 5. RESOURCE, ADMINISTRATION, COMMUNICATIONS & WORKSHOP PLANS

CanSISE features an unusual degree of cross-coordination of research between the University and GoC Sectors, and a strong commitment to four distinct Deliverables that will benefit our research partners and the broader public. CanSISE has established an organizational structure and schedule in order to achieve its ambitious aims. PK leads the CanSISE SC, which consists of SD, GF, JF, CH, WM, and FZ and includes representation in all the Research Areas and Deliverables. In development of this proposal, the SC, via email and biweekly teleconferences in August and September, has worked very effectively in the development in setting a budget and overall strategic direction. Going forward, the SC will be responsible for HQP recruitment, strategic direction, project planning, and budget planning. In consultation with the broader network and the Advisory Panel, the SC will deal with Workshop organization, travel and other resource spending, priorities for analysis and simulation, and evaluation of application for the HQP positions advertised by the Network.

Most HQP positions will be advertised centrally through the Network and applications viewed and discussed by Network membership. Graduate studentships will also be advertised through the Network but graduate student appointments will depend upon individual University admissions. The CanSISE Network will feature a unique competitive undergraduate programme called the *CanSISE Undergraduate Student Internship Programme*, administered by the SC. For this programme, CanSISE will call for applications and select two undergraduate student applicants each summer. These students will be appointed to 12-16 week summer internship positions with members of the Network. Travel and equipment funding will be administered through the SC (funds will be in accounts at Toronto) and allocated as fairly as possible to the Network.

The activities of the network will be organized around three Network Workshops (see Table below), to which all Network membership and partners will be invited. The Workshops will include research reports, deliverable reports, and administrative meetings. The Advisory Panel will be asked to attend Workshops 1 and 3 and invited as they are available for Workshop 2. In addition, the SC will convene ½ day meetings by video- or tele-conference in Years 2 and 4. Network workshops will also include planning meetings with applicants, EC partners, and RAs.

Day-to-day support administration of the Network will be handled through PK, a half-time administrator at Toronto, Res. Assoc. 1 (Victoria, Years 1-5) and Res. Assoc. 2 (Toronto, Years 3-5). Data used by the workshop will be distributed to the network via two data/compute servers, one located in Victoria and one in Toronto. All network members will be permitted to have accounts on these machines, which will be used as an access point for model output and observational data products. Model output and observational data products will be shared on request subject to the restrictions of the data providers, primarily EC.

Dissemination will be via reports to EC (for the Deliverables), conference presentations, and quality articles in peer reviewed high impact journals. Most communications with the Network and the public will be via a content management system based website hosted at the Department of Physics at the University of Toronto. Deliverables will be linked to the three planned Network Workshops that all Network members will be expected to attend. Network members will also be encouraged to convene sessions explicitly linked to the Network research areas at major international meetings each year.

Workshop	**Tentative Schedule**
Workshop 1, February 2014, Victoria (3 days)	• Research Areas Reports (Day 1), Deliverables Reports (Day 2), Steering Committee and Advisory Panel Meeting (Day 3) • *Deliverable 1 Focus*: Status of S/SI simulations in the Canadian models. CanSIPS S/SI performance assessmnt. Development of standard diagnostic analysis report. Preliminary look at predictions and forecasts from CanSIPS.
Workshop 2, February 2016, Toronto (2.5 days)	• Research Areas Reports (Day 1), Deliverables Reports (Day 2), Steering Committee Meeting and Advisory Panel telecon (half day on Day 3) • *Deliverable 2 Focus*: S/SI Predictions to 2025 • *Deliverable 3 Focus*: Preliminary report on 2012 sea ice events.
Workshop 3, October 2017, Victoria (3 days)	• Research Area Review (Day 1), Deliverables Reports (Day 2), Steering Committee and Advisory Panel Meeting (Day 3) • *Deliverable 1 Update:* Changes of simulation of S/SI in the Canadian models. • *Deliverable 3 Focus*: Attribution of Cryospheric Events of 2007 and 2012 • *Deliverable 4 Focus*: CanSISE report on design of future observational networks.

Section 6. HQP TRAINING

CanSISE is designed to create an outstanding group of emerging scientists who will possess a multi-faceted understanding of S/SI and the role they play in climate and the water cycle. The Network will provide a combination of specialized and broad training that will lead to effective research and problem solving skills in climate analysis, climate monitoring, seasonal and interannual prediction, hydrology, and water resource science. Presentation skills gained in the Network will teach our trainees to be effective communicators so that their research results can have the broadest impact on academia, industry and government. The most basic goal of CanSISE is for all trainees to acquire a fundamental scientific understanding of the climate system and the atmospheric and hydrological sciences.

Over the next five years we expect to involve 32 students, postdoctoral fellows and research associates/assistants as part of CanSISE. Some positions are expected to span the duration of the network (e.g., the research assistants) while others will be for shorter terms (e.g., the summer undergraduate student positions). All network members are expected to contribute to the training of HQP across all three Research Themes to achieve the four Deliverables. Our proposed mix of trainees across all scholarly levels will ensure effective mentorship and mutual training by the HQP themselves. In turn, supervisors will develop more effective training and communication skills as well as scientific insight through the HQP's research findings. Many of the trainees will be co-supervised by mentors at multiple institutions, ensuring all involved broader exposure. Collaborative visits to the CCCma, EC Downsview, PCIC and with EC scientists at Ouranos will provide trainees further opportunities to enhance their understanding of climate models and the simulations they produce. Thus HQP will play a key role in facilitating knowledge and technology transfer to institutions such as EC and PCIC. In addition, each trainee will link researchers in one region but will also have cross-regional ties.

Trainees will be directly involved in all areas of the research proposed for the CanSISE network. Research associates/assistants will also be trained within the network and will provide technical and managerial support to the researchers in addition to performing research duties. Apart from their research, they will also contribute to the preparation of annual reports, network website development, and database management. Undergraduate students will also be engaged in research as summer interns, providing them unique opportunities in the setting of a research network. These internships will be established through the *CanSISE Undergraduate Internship Programme* (Section 5).

The complexity of the problems in climate science and hydrology we are addressing require students and postdoctoral fellows to receive interdisciplinary training that emphasizes solutions-based research. Another objective of CanSISE is therefore to guard against the 'silo effect' by requiring strong co-supervised partnerships and collaborative visits. This allows our trainees to overcome the limitations of expertise found in any one university or government laboratory department. We will endeavour to provide these trainees with fruitful collaboration and mentorship, and foster the successful exchange of students, ideas, and ultimately, innovation.

CanSISE trainees will gain professional skills in addition to becoming well-rounded specialists in cryospheric science. The CanSISE workshops will provide trainees with a forum for effective knowledge exchange, an opportunity to pool their experiences to achieve a common goal, and a chance for personal growth and development. Beyond the workshops, trainees will be expected to disseminate their research results in various fora. They will attend national and international conferences to present their work, publish results in high impact journals, and meet fellow members of the scientific community as part of their training to become critical thinkers and accomplished researchers. They will also be encouraged to participate in community outreach activities for further dissemination of their work. Network resources are being set aside to support all of these HQP activities (see budget tables).

A significant measure of the success of CanSISE will be the extent to which it provides opportunities for employment in the private and government sectors. Our GoC partners are enthusiastic to support our training and research opportunities program in Canadian cryospheric sciences through internships and term employment. The letter of support from EC affirms the willingness of our collaborators to adequately prepare our trainees for future career placements in industry and government agencies. We expect that many of our trainees will pursue productive careers as Canadian academics specializing in cold-climate and cryospheric science while others will be employed by the private sector. In the end, we envision that the majority of our trainees will work as professors, meteorologists, numerical modellers, hydrologists, and ice experts with a strong research focus on the cryosphere.

1 Alexander, Michael, et al, 2002, J Clim, 15, 2205–2231.
2 Barnett, Pierce, et al, 2008, Science, 319, 1080-1083, doi: 10.1126/science.1152538.
3 Berg, Famiglietti, et al, 2003, J Geophys Res, 108, 4490, doi:10.1029/2002JD003334.
4 Berg, Famiglietti, et al, 2005, Intl J Clim, 25, 1697-1714, doi:10.1002/joc.1203.
5 Bitz, Fyfe, and Flato, 2002, J Clim, 15, 522–536.
6 Boé, Hall, et al, 2010, Clim Change, 99, 637-64, doi:10.1007/s10584-010-9809-6.
7 Boer and Lambert, 2008, Geophys Res Lett, 35, L05706, doi:10.1029/2008GL033234.
8 Boer, 2000, Clim Dyn, 16, 469-477.
9 Boer, 2004, Clim Dyn, 23, 29-44, doi:10.1007/s00382-004-0419-8.
10 Boer, 2009, J Clim, 22, 3098-3109, doi:10.1175/2008JCLI2835.1.
11 Boer, 2010, Clim Dyn, doi:10.1007/s00382-010-0747-9.
12 Brasnett, 1999, J Appl Meteor, 38, doi:10.1175/1520-0450(1999)038<0726:AGAOSD>2.0.CO;2.
13 Brown and Robinson, 2011, Cryosphere, 5, 219-229. doi:10.5194/tc-5-219-2011.
14 Brown, Derksen, and Wang, 2010, J Geophys Res, 115, D16111, doi:10.1029/2010JD013975.
15 Budyko, 1969, Tellus, 21, 611–619, doi:10.1111/j.2153-3490.1969.tb00466.x.
16 Buerger, Murdock, et al, 2012, J Clim, 25, 4366-4388, doi: 10.1175/JCLI-D-11-00408.1.
17 Cavalieri, Markus, et al, 2012 IEEE TGRS, 50, 8, doi:10.1109/TGRS.2011.2180535.
18 Cohen and Entekhabi, 1999, Geophys Res Lett, 26-345-348.
19 Cohen and Fletcher, 2006, J Clim, 20, 4118-4132, doi:10.1125/JCCI14241.1.
20 Derksen and Brown, 2012, Geophys Res Lett, in press, doi:10.1029/2012GL053387.
21 Derksen, Smith, et al, 2012, Clim Change, doi:10.1007/s10584-012-0470-0.
22 Déry and Brown, 2007, Geophys Res Lett, 34, L22504, doi:10.1029/2007GL031474.
23 Déry, Stahl, et al, 2009, Water Resour Res, 45, W04426, doi:10.1029/2008WR006975.
24 Deser, Tomas, et al, 2010, J Clim, 23, 2, 333–351, doi:10.1175/2009JCLI3053.1.
25 Drewitt, Berg, WM, et al, 2012, Atmosphere-Ocean, accepted.
26 Fernandes, Zhao, et al, 2009, Geophys Res Lett, 36, L21702, doi:10.1029/2009GL040057.
27 Flanner, Shell, et al, 2010, Nature Geo, 4, 151-155, doi:10.1038/ngeo1062.
28 Flato and Hibler, 1992, J Phys Oceanogr, 22, 626–651.
29 Fletcher, Kushner, et al, 2009, Geophys Res Lett, 36, L09702, doi:200910.1029/2009GL038011.
30 Fletcher, Zhao, PK, et al, 2012, J Geophys Res.-Atmos, 117, doi:10.1029/2012JD017724.
31 Fyfe and Flato, 1999, J Clim, 12, 230-243.
32 Fyfe, Merryfield, SK, GB, et al, 2011, Geophys Res Lett, 38, L22801.
33 Gillett and Stott, 2009, Geophys Res Lett, 36, L23709, doi:10.1029/2009GL041269.
34 Griffies and Bryan, 1997, Clim Dyn, 13, 459-488, doi:10.1007/s003820050177.
35 Hall, 2004, J Clim, 17, 1550–1568.
36 Hardiman, Kushner, and Cohen, 2008, J Geophys Res, 113, doi:10.1029/2008JD010623.
37 Hegerl and Zwiers, 2011, WIREs Clim Change, 2, 570-591, doi:10.1002/wcc.121.
38 Hegerl, Hoegh-Guldberg, et al, 2010, IPCC WG I.
39 Hegerl, Zwiers, et al, incl. NG, 2007, IPCC AR4.
40 Hoerling, Hurrell, et al, incl. LT, 2011, J Clim, 24, 4519-4528, doi:10.1175/2011JCLI4137.1.
41 Holloway and Sou, 2002, J Clim, 15, 1691–1701.
42 Howell, Duguay, and Markus, 2009, Geophys Res Lett, 36, L10502.
43 Howell, Tivy, et al, 2008, J Geophys Res, 113, C09030, doi:10.1029/2008JC004730.
44 Hsieh, 2009, Machine Learning Methods in the Environmental Sciences. Camb Univ Pr., 349 pp.
45 Jin and Kirtman, 2010, Clim Dyn, 34, 935-951, doi:10.1007/s00382-009-0600-1.
46 Jones, Lister, et al, 2012, J Geophys Res, 117, D05127, doi:10.1029/ 2011JD017139.
47 Kharin, Boer, WM, et al, 2012, Geophys Res Lett, accepted.
48 Koster, Mahanama, et al, incl. AB, WM, 2010, Geophys Res Lett, 37, L02402.
49 Koster, Mahanama, et al, incl. AB, WM, 2011, J Hydrometeor, 12, 805-822.
50 Kwok and Rothrock, 2009, Geophys Res Lett, 36, L15501, doi:10.1029/2009GL039035.

51 Kwok, Cunningham, et al, 2009, J Geophys Res, 114, C07005, doi:10.1029/2009JC005312.
52 Kwok, Panzer, et al, 2011, J Geophys Res, 116, C11018, doi:10.1029/2011JC007371.
53 Lemieux and Tremblay, 2009, J Geophys Res, 114, C05009, doi:10.1029/2008JC005017.
54 Lemieux, Tremblay, et al, 2008, J Geophys Res, 113, C10004, doi:10.1029/2007JC004680.
55 Lemieux, Tremblay, et al, 2010, J Comp Phy, 229, 2840.
56 Liang, Lettenmaier, et al, 1994, J Geophys Res, 99, D7, 14,415-14,428.
57 Liu, Schmidt, et al, 2003, J Geophys Res, 108, C2, 3053, doi:10.1029/2001JC001167.
58 Ma, 2010, PhD Thesis, York University.
59 Markus, Stroeve, and Miller, 2009, J Geophys Res, 114, C12024, doi:10.1029/2009JC005436.
60 Masutani, Woollen, et al, 2010, J Geophys Res, 115, D07101, doi:10.1029/2009JD012528.
61 McPhee, Kwok, et al, 2005, Geophys Res Lett, 32, L10616, doi:10.1029/2004GL021819.
62 Merryfield, Denis, et al, incl. SK, 2011, CanSIPS: An Overview.
63 Merryfield, Lee, GB, SK, et al, incl. GF, JF, 2012, Mon Wea Rev, submitted.
64 Min, Zhang, FZ, et al, 2008a, Science, 320, 518-520, doi:10.1126/science.1153468.
65 Min, Zhang, FZ, et al, 2008b, Geophys Res Lett, 35, L21701, doi:10.1029/2008GL035725.
66 Nguyen, Menemenlis, and Kwok, 2009, J Geophys Res, 114, C11014.
67 Orsolini and Kvamsto, 2009, J Geophys Res-Atmos, 114, doi:10.1029/2009JD012253.
68 Perovich, Nghiem, et al, 2007, J Geophys Res, 112, C03005, doi:10.1029/2006JC003558.
69 Qu and Hall, 2007, J Clim, 20, 3971–3981, doi:10.1175/JCLI4186.1.
70 Rayner, Parker, et al, 2003, J Geophys Res, 108, D14, 4407, doi:10.1029/2002JD002670.
71 Ribes, Azaïs, and Planton, 2010, Clim Dyn, 391-406, doi:10.1007/s00382-009-0670-0.
72 Ribes, Planton, and LT, 2012, Clim Dyn, submitted.
73 Rigor, Wallace, et al, 2002, J Clim, 15, 2648-2663.
74 Robinson, Dewey, et al, 1993, Bull Amer Meteor Soc, 74, 1689-1696.
75 Scherrer, Ceppi, et al, Theor Appl Climatol, in press.
76 Screen and Simmonds, 2010, Nature, 464, 1334-1337.
77 Screen, Deser, Simmonds, 2012, Geophs Res Lett, 39, L10709, doi:10.1029/2012GL051598.
78 Serreze and Francis, 2006, Clim Change, 76, 241-264.
79 Serreze, Mark, et al, 2008, J Clim, 21, 1048–1065.
80 Serreze, Mark, et al, 2011, J Clim, 24, 159–182.
81 Sheffield, Goteti, et al, 2006, J Clim, 19, 3088-3111, doi:10.1175/JCLI3790.1.
82 Shin and Sardeshmukh, 2010, Clim Dyn, 36, 1577-1591, doi:10.1007/s00382-009-0732-3.
83 Shrestha, Schnorbus, et al, 2012, Hydrol Processes, 26, 1840-1860, doi:10.1002/hyp.9283.
84 Sou and Flato, 2009, J Clim, 22, 2181–2198, doi:10.1175/2008JCLI2335.1.
85 Stahl and Moore, 2006, Water Resour Res, 42, W06201, doi:10.1029/2006WR005022.
86 Steffen and Schwieger, 1991, J Geophys Res, 96, C12, 21,971-21,988.
87 Stott, Stone, et al,, 2004, Nature, 432, 610-614, doi:10.1038/nature03089.
88 Stroeve, Holland, et al, 2007, Geophys Res Lett, 34, L09501, doi:10.1029/2007GL029703
89 Stroeve, Kattsov, et al, 2012, Geophys Res Lett, 39, L16502, doi:10.1029/2012GL052676.
90 Stroeve, Serreze, et al, 2011, Clim Chang, doi:10.1007/s10584-011-0101-1.
91 Takala, Luojus, et al, incl. CD, 2011, Remote Sens Environ, 115, 12, 3517-3529.
92 Taylor, Stouffer, et al, 2012, Bull Amer Meteor Soc, 93, 485-498.
93 Thorndike and Colony, 1982, J Geophys Res, 87, C8, 5845–5852.
94 Tivy, Howell, et al, 2011, J Geophys Res, 116, C03007, doi:10.1029/2009JC005855.
95 Vose, Schmoyer, et al, 1992, CDIAC Communications, 17, doi:10.3334/CDIAC/cli.ndp041.
96 Wan, Zhang, FZ, et al, 2012, J Geophys Res, submitted.
97 Wohlleben, Howell, et al, 2012, Atmos-Ocean, in press.
98 Wood and Lettenmaier, 2006, Bull Amer Meteor Soc, 87, 1699-1712.
99 Zhang, Zwiers, et al, incl. NG, 2007, Nature, 448, 461-465, doi:10.1038/nature06025.