Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)
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THE PUBLIC PART OF THE FINAL REPORT FOR THE DROUGHT RESEARCH INITIATIVE (DRI)

DRI Co-Investigators: Prof. Ronald Stewart and John Pomeroy

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DRI Final Report

Project Title: Drought Research Initiative

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1. Introduction

Drought is a fundamental aspect of the climate system. Droughts are recurring aspects of weather and climate extremes, as are floods and tornadoes, but they differ substantially since they have long durations and generally lack easily identified onsets and terminations. Geographically, drought is a relatively common feature of the North American and Canadian climate system. However, it tends to be most common and severe over the central regions of the continent, including the Canadian Prairies.

Droughts on the Canadian Prairies have their own unique features. The large-scale atmospheric circulations are influenced by blocking from high terrain to the west and long distances from all warm ocean-derived atmospheric water sources. Growing season precipitation is generated by a highly complex combination of frontal and convective systems often enhanced by moisture recycling over vegetated surfaces. In these areas, seasonality is forced by relatively long snow-covered and short growing seasons. Furthermore, local surface runoff is frequently dominated by snowmelt water which moves over soils in the poorly drained, post-glacial geomorphology. A major multi-year Prairie drought that was strongly influenced by all of these processes began in 1999. Its atmospheric component ended in 2004 and 2005 and many of its hydrological components ceased in 2005.

The 1999-2005 drought affected agriculture, recreation, tourism, health, hydroelectricity, and forestry across the Prairies. This drought also contributed to a negative or zero net farm income for several provinces for the first time in 25 years, with agricultural production over Canada dropping by an estimated $3.6 billion at its peak in 2001 and 2002. The Gross Domestic Product fell by approximately $5.8 billion during the same period. Employment losses exceeded 41,000 jobs for 2001 and 2002. Previously reliable water supplies such as streams, wetlands, dugouts, reservoirs, and groundwater were placed under stress and often failed. For example, the number of natural Prairie ponds documented in May 2002 was the lowest on record.

After the major drought of 1999-2005, the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) issued a call for proposals. Several atmospheric scientists, most notably Ron Stewart and Barrie Bonsal, joined forces with members of the hydrologic sciences community, led by John Pomeroy, and developed a proposal to study the drought. In late 2005, the proposal was approved and in early 2006 the DRI research network began to function as funds were distributed and Investigators initiated their projects.

In developing the proposal many questions about different aspects of the drought were uncovered. There were questions about why the drought lasted so long and why its final demise could not have been predicted with more accuracy. Many people wanted to know how this drought compared to earlier droughts and if it signalled a change in the climate. The scope of many of these questions was captured in the overall DRI objective: “to better understand the physical characteristics of and processes influencing Canadian prairie droughts, and to contribute to their better prediction, through a focus on the recent severe drought that began in 1999 and largely ended in 2005".

To address its overall objective, the DRI Network has focused on five research themes and their objectives, namely to:

- quantify the physical features of this recent drought;
- improve the understanding of the processes and feedbacks governing the formation, evolution, cessation, and structure of the drought;
- assess and reduce uncertainties in the prediction of drought and its structure;
- compare the similarities and differences of the recent drought to previous droughts over this region and those in other regions in the context of climate variability and change; and
- apply our progress to provide advice on how to mitigate the impacts of drought in the future.

Initially, all the funding for DRI came from the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS). Although CFCAS has remained the primary source of funding for DRI throughout the project, many scientists had a need for more funding to expand their investigations and found ways to obtain other direct funding or in-kind contributions from a number of federal and provincial government departments. The opportunity to mobilize these contributions and to generate multiplier or leverage effects is one of the advantages of working with a CFCAS network.

This report is the final report for DRI. It builds on the five earlier annual reports and addresses some issues that are unique to the end of the project.

While DRI has not yet solved all of the problems associated with drought, DRI Investigators believe that their research provides much of the necessary scientific underpinning needed to credibly address the longer-term goals of drought research, namely:

- To better predict droughts over Canada, their detailed structure, and their impacts with increasing confidence; and
- To better assess whether there will be a drying of the continental interior in the future.

2. **Overview by DRI Management** (Ronald Stewart, John Pomeroy, Rick Lawford)

The progress of the DRI programme can be classified into three distinct phases: the initiation, maturation and legacy phases. During the project initiation phase, which lasted from 2006 to 2007, considerable effort was placed on data acquisition. To a large degree the project relied on datasets that had already been collected, and as a result the Data Managers were very active in assisting Investigators in accessing the datasets that were needed for their projects. The Data Analysis and Integration (DAI) system was central to this activity and housed many of the datasets that were needed by DRI Investigators. Between 2007 and 2009, analysis and modelling were carried out and many new ideas emerged from the research activity as projects matured. The legacy phase, which began in 2009, focused on publishing these results, incorporating them into overall syntheses of the phenomenon and using the results in applied formats so they would be of greater relevance to users.

DRI Investigators contributed during the legacy period by reviewing their datasets and providing them to the Western Data Manager. Most DRI Investigators have been contributing to one or more of the synthesis articles that are in preparation as one of the DRI legacies. Synthesis studies provided new perspectives and identified gaps in understanding and relationships that support the original goal of DRI for an integrated study. Highlights of this scientific progress are given in the Theme summaries, while details of the discoveries by DRI Investigators are available in the Appendices in the full report. The corporate component and the DRI Secretariat have been facilitating this shift in perspective by promoting the DRI legacy and supporting the conduct of a number of focused workshops. The Drought Characterization Study (Theme 1) made impressive strides during the last two years of DRI, developing a synthesized view of the drought. Investigators also have made notable research advances in Theme areas 2 and 3. It was anticipated as we moved from the Project Mature stage to the Project Legacy stage that the emphasis would also shift from Theme 1 to Theme 3 issues and goals. While this shift did take place at one level, the overall project tended to place a greater emphasis on Themes 1 and 2 than on Theme 3.

Overall Assessment and Research Highlights:

DRI has made substantial progress in identifying ways to monitor drought in an integrated way. Theme 1 made excellent progress in developing a synthesized view of the 1999-2005 drought. Data analysis was carried out in order to fill some of the gaps in the preliminary analysis of the outputs of individual Investigators as well as to undertake additional analysis to gain a better understanding of how the drought evolved. Theme 2 provided insights into a number of processes. This new understanding was used to improve a number of hydrologic models. In particular, DRI has been successful at developing an understanding of the "fill and spill" process and models to deal with non-contributing areas. This includes improving models of the progression of water from wetland to wetland in linked systems commonly considered as non-contributing areas. Theme 3 assembled a large number of model data sets. It is poised to assess the skills in prediction capabilities and to take steps to improve those skills. This theme continues to make progress in the improved representation of hydrological processes in groundwater and land-surface models. As a result of progress in Theme 4, a project is under way to study droughts in their full transition from historical events and current events to the types of events that could be expected under climate change scenarios. Through the planning of the Partners Advisory Committee (PAC) and the DEWS (Drought Early Warning System) exercises, Theme 5 has initiated a vigorous dialogue with stakeholders and the user community. This final report documents the degree to which these activities have contributed to DRI's overall goals in the framework of the CFCAS reporting template.

Led by Dr. John Hanesiak, Theme 1 focused on the development of a synthesis of information about drought. This synthesis has brought together many disciplinary perspectives on drought and has advanced our understanding of the interaction among fields such as meteorology, hydrology and agricultural sciences. It has been complemented by a diverse set of studies, including one on the linkages between elements such as drought indices and grain quality, and another on the effects of data sources on values of drought indices. This exercise has identified gaps and limitations in the current suite of products available for drought monitoring. This assessment has enabled DRI to provide feedback to the North American Drought Monitor (NDAM) activities and the global drought monitoring plan being proposed under the Group on Earth Observations (GEO) about more reliable ways to monitor drought. A DRI workshop on precipitation, held at the Meteorological Service of Canada (MSC) in Downsview, Ontario in the spring of 2009, emphasized the need to maintain the observational network and ensure that high-quality data are made available to users as quickly and economically as possible.

Theme 2, which addressed the need for better process understanding, advanced through data analysis, targeted field campaigns and experiments and process model studies. This theme progressed under the overall leadership of Dr. Masaki Hayashi (University of Calgary), assisted by Dr. Barrie Bonsal (University of Saskatchewan), who provided support on the atmospheric side. A major challenge for this theme is the need to integrate process understanding across scales and media (groundwater, land and atmosphere). Several projects study the large-scale atmospheric processes and patterns that lead to precipitation deficits on the Canadian Prairies. Teleconnection patterns alone are not sufficient to understand the formation and dissipation of droughts. While flow regimes associated with larger teleconnection patterns control the placement of the jet stream and the upper ridge over Western Canada, the Pacific North American (PNA) patterns, strong moisture jets from the Pacific (such as the Pineapple Express) and the western Cordillera all play a role in producing circulation regimes that enhance or inhibit the formation of precipitation over the Canadian Prairies. Surface forcing in the foothills of the mountains can also trigger the redistribution of moisture through convective events (especially thunderstorms). Studies of evapotranspiration (ET) and soil moisture are also important to understanding land, groundwater and atmosphere feedbacks. The changes in hydrological processes of snow redistribution, sublimation, melt, infiltration to frozen soils, evapotranspiration and spring runoff generation associated with drought progression have been described for the first time. In some areas, such as the Assiniboine Delta Area (ADA), in which soils are very sandy, the influence of groundwater on evapotranspiration is also being measured and modelled.

Theme 3, which was led by Dr. Charles Lin (Environment Canada, McGill University), made significant progress in several important areas of DRI. Research related to the theme has involved the development of model data products and the assessment of model outputs, ensemble approaches to the estimation of fluxes feedback processes and model development. The overall goal of Theme 3 involves an evaluation of model outputs to assess how well current models predict drought and which steps should be taken in order to improve their ability to predict. It also improved models' ability to simulate drought impacts and to evaluate the benefits of improving parameterizations that have been calibrated or designed for drought conditions. In addition, it assessed which features of a prediction model had to be enhanced to enable them to better predict droughts in the future. Advances were made in evaluating and improving both atmospheric and hydrologic prediction systems through the examination of model simulations and modelling studies. The simulation and prediction of cloud and precipitation are central issues for drought research.

The "fill and spill" modelling system has been a major breakthrough that allows us to monitor the movement of water in non-contributing areas. The Cold Regions Hydrological Model (CRHM) provided the first comprehensive simulations of Prairie hydrology for upland and wetland basins, including identification of a memory effect that reduces the impact of drought on surface water supplies where wetland systems are intact in drainage basins. In addition, new parameterizations for these areas have enabled DRI to use the Variable Infiltration Capacity (VIC) model to produce historical and real-time estimates of soil moisture for the three Prairie Provinces. Soil moisture assimilation is an important aspect of this theme, thanks to collaborations with Dr. Aaron Berg and a project on soil moisture assimilation in Numerical Weather Prediction (NWP) Models. A new version of the Canadian Land Surface Scheme (CLASS) model, gCLASS, was developed and calibrated for simulating the interactions of groundwater and the atmosphere in areas in which the high permeability of soils results in landscapes that are not conducive to producing surface runoff (areas such as the ADA).

Although there was no funding for Themes 4 and 5, DRI has made a number of "best effort" contributions and influenced others to make progress on these research topics. Theme 4 made progress in developing a comparative analysis of droughts in paleoclimatological records, historical instrumental records and climate change scenarios. DRI strengthened its collaborations with Agriculture and Agri-Food Canada (AAFC) and discussed drought policy issues with provincial agencies through a series of user workshops and the DEWS exercises. AAFC has launched a "drought tournament" as a result of its collaboration with DRI. DRI also contributed to model development and analysis activities that have led to improvements in provincial drought information services.

Secretariat Update:

The Secretariat has served as the executive arm for the project in terms of helping to implement decisions made by the Science Committee and Board of Directors, meeting the reporting requirements of CFCAS, organizing and monitoring finances and deliverables, delivering data and web services and providing many of the corporate and network functions for DRI. For example, the Network Manager organized and summarized actions from monthly teleconference calls of the DRI Science Committee (chaired by Ron Stewart), the Board of Directors (chaired by Jim Bruce), and PAC (chaired by Harvey Hill). As opportunities arose, the Secretariat also promoted DRI through talks and participation in external workshops and working groups, such as meetings of the Canadian GEO activities, coordinating workshops, interacting with Partners and Stakeholders, and maintaining and developing the website and data systems. The Secretariat's staff changed over the course of the project. This was in part related to Prof. Stewart's move from McGill University to the University of Manitoba during the course of DRI. Table 1 provides a summary of the personnel who served in the Secretariat.

Network Manager:	Geoff Strong – January 2006 to July 2006
	Rick Lawford – August 2006 to March 2011
Financial Manager:	Shelley Rooney – January 2006 to January 2008
	Rachael Reynen – February 2008 to March 2010
	Rebecca Hargreaves – April 2010 to September 2010
	Guiseppe Tognanni – October 2010 to December 2010
	Jennifer Marleau – January 2011 to March 2011
DRI Data Manager East:	Patrice Constanza – January 2006 to March 31, 2011
DRI Data Manager West:	Matt Regier – January 2006 to July 2007

Phillip Harder – October 2008 to March 2011

DRI Webmaster: Peter Lawford – July 2007 to March 2009

The Secretariat supported the development of several proposals, including the following:

- The successful proposal to CFCAS for the DEWS, a Western Canada Data Manager and the GEO-DRI Workshop.
- A proposal to GEO for the DRI data legacy to serve as a prototype Group on Earth Observations System of Systems (GEOSS) architecture for data systems supporting limited-term research projects with high data volumes. The proposal was accepted by GEO although no funding was associated with it.
- A successful proposal to CFCAS for a series of public lectures and a joint workshop between GEO and DRI.
- The Secretariat also had peripheral involvement in several other proposals, including a proposal to enhance drought prediction.

Phillip Harder led the development of the DEWS presentation, a "table-top" exercise to assess the potential value of new research products for users. The first DEWS exercise was held with Saskatchewan users in conjunction with the 2009 DRI Annual Workshop in Regina. Phillip Harder and Patrice Constanza also developed a DRI data legacy policy that has been approved by the DRI Science Committee. Subsequently, Phillip Harder contacted each DRI Investigator, asking them to submit their metadata and data. Most Investigators have complied with this request.

The DRI Science Committee

This Committee was the central decision-making body in DRI. It met by teleconference every month and in person once per year. In general this committee reviewed inputs for CFCAS and made recommendations on program changes before they were passed on to the Board of Directors. Issues that were dealt with by this Committee included planning meetings and workshops, reviewing and approving reports, developing and implementing recommendations when corrective action was required in specific projects and allocating funds to Investigators for special projects. Members of the DRI Science Committee include:

Barrie Bonsal, University of Saskatchewan
John Hanesiak, University of Manitoba
Masaki Hayashi, University of Calgary
Charles Lin, McGill University
John Pomeroy, University of Saskatchewan
Ken Snelgrove, Memorial University
Ronald Stewart (Chair), University of Manitoba/ McGill University
Kit Szeto, Environment Canada
Elaine Wheaton, University of Saskatchewan
Al Woodbury, University of Manitoba
Ex-officio: Patrice Constanza, McGill University
Ex-officio: Phillip Harder, University of Manitoba
Ex-officio: Rick Lawford, University of Manitoba

The Board of Directors and the Partners Advisory Committee met less regularly than the Science Committee. The Board of Directors approved annual budgets, plans and reports. They also provided strategic guidance on the programme and assisted with the Initiative's image and outreach. Members of the Board of Directors included:

Jim Bruce (Chair), Consultant
Harvey Hill, Agriculture and Agri-Food Canada
Gary Burke (2006-2008) and Bob Kochtubajda (2009-2011), Environment Canada (MSC)
John Pomeroy, University of Saskatchewan
Ronald Stewart, University of Manitoba/ McGill University
Ex-Officio: Tim Aston, CFCAS
Ex-Officio: Rick Lawford, University of Manitoba

The Partners Advisory Committee provided an independent review of user needs and research requirements to the DRI Board of Directors. They were also responsible for planning the Provincial User Workshops and other user interactions. Members of the Partners Advisory Committee included:

Bill Girling, Manitoba Hydro
Irene Hanuta, Agriculture and Agri-Food Canada
Harvey Hill (Chair), Agriculture and Agri-Food Canada
Daniel Itenfisu, Alberta Agriculture and Food
Rick Lawford, University of Manitoba
Andrew Nadler, Manitoba Agriculture, Food and Rural Initiatives
Bart Oegema, Saskatchewan Watershed Authority
Alf Warkentin, Manitoba Water Stewardship
Elaine Wheaton, Saskatchewan Research Council

Outreach and Coordination Activities:

DRI held five annual workshops, which on average attracted 70 participants. Attendees included Investigators and Collaborators, graduate students, Stakeholders and users of DRI products. The workshops were held at the following times and in the following cities:

Annual Workshop 1 – Saskatoon – January 11-12, 2006
Annual Workshop 2 - Winnipeg – January 11-13, 2007
Annual Workshop 3 – Calgary – January 17-19, 2008
Annual Workshop 4 – Regina – January 26-28, 2009
Annual Workshop 5 – Winnipeg – May 12-14, 2010

For some of these workshops a press release was issued, while for others an updated statement on DRI progress was added to the website. These workshops provided feedback to the Investigators on their research, since the Science Committee, the Partners Advisory Committee and the Board of Directors usually met at these meetings. The presentations from these workshops are available at www.drinetwork.ca.

Communication between DRI Investigators and between the DRI Secretariat and the Investigators was facilitated by the DRI website, teleconference calls and the list serve feature, which allowed for regular mail-outs to the Investigators The entire DRI community interacted at annual planning meetings and at thematic workshops held throughout the duration of the project. The thematic workshops included:

- The DRI Evaporation Workshop held in Saskatoon on May 17, 2007
- A Drought Characterization workshop held in Winnipeg on September 26, 2008
- A Precipitation and Drought Indices workshop held in Downsview, Ontario on April 30, 2009
- The DRI prediction workshop held in Montreal on September 28, 2009
- The Prairies Drought Hydrology workshop held on November 18, 2009
- A GEO-DRI workshop held in Winnipeg on May 10-11, 2010
- A synthesis workshop held on February 10-11, 2010 in Winnipeg to discuss the ways to bring information together for synthesis papers
- A CFCAS workshop on data management held in Winnipeg on November 20, 2009
- An Extremes workshop held in Winnipeg on February 7-9, 2011

An affiliated workshop, mainly funded by the Natural Sciences and Engineering Research Council (NSERC), was the May 2009 Research for Disaster-reduction from Extremes (REDE) Workshop in Winnipeg, which drew on the participation of the DRI science community.

In addition to its meetings and workshops, the DRI project gained visibility through presentations at a number of meetings, generally in response to requests for invited talks. For example, talks on DRI were given by the Principal Investigators (PIs), the Network Manager and the Data Managers at Canadian Meteorological and Oceanographic Society (CMOS) meetings, Canadian Geophysical Union (CGU meetings, American Geophysical Union (AGU) meetings, the Improved Processes and Parameterisation for Prediction in Cold Regions (IP3) and Western Canadian Cryospheric Network (WC2N) science meetings, the North American Drought Monitoring meeting, a Chinese Academy of Sciences arid climate symposium, workshops held in conjunction with the 2010 GEO Summit in Beijing, a Middle East speaking tour (Libya, Kuwait, Lebanon) funded by Foreign Affairs and International Trade Canada (DFAIT) and at a European Drought study meeting.

Partners and Stakeholders:

The Partners Advisory Committee was established in 2007 to improve interaction between DRI and the user and stakeholder community. The committee was chaired by Harvey Hill of AAFC and included representatives from Alberta Agriculture, Alberta Environment, the Saskatchewan Watershed Authority, the Saskatchewan Research Council, Manitoba Water Stewardship, Manitoba Agriculture, Agriculture and Agri-Food Canada and Canadian GEO. This Committee was mandated to provide advice to the DRI Board of Directors on how the project can more effectively address the needs of its stakeholders and users. Activities initiated and undertaken by this Committee included a survey of user needs for drought information and a recommendation for DRI to undertake a series of workshops with users.

The DRI Legacy:

During the last year-and-a-half of the project, DRI has made substantial progress in developing its legacy. This legacy has four main pillars, including:

1) DRI Data Legacy
   This legacy involves a data system that will meet the needs of future drought researchers by providing the most comprehensive database available on the Canadian Prairies 1999-2005 drought. The data system will have both a centralized and distributed component so that researchers can access information from individual scientists. More details on this data legacy are given in Section 7.3.

2) DRI Special Issue of *Atmosphere-Ocean*
   This special issue will consist of a number of scientific and synthesis articles, including an overall synthesis of the findings of DRI. The major synthesis article is John Hanesiak's drought characterization article.

3) The Lecture Series
   Prof. Ronald Stewart has toured a number of major centres across Canada to give lectures on drought, extremes and climate change. As noted earlier, funding for these lectures was provided by a special grant from CFCAS.

4) The DRI Professional Document
   A report, modelled after a similar publication prepared by GEO for its Ministerial Summit in 2007 entitled *The Full Picture,* has been developed to document the research discoveries and scientific successes of DRI in layman's terms. This publication will be a primary source of information for Canadians interested in drought research. After an initial distribution of copies, they will be available through Ronald Stewart.

5) The DRI Evaporation Special Issue of the *Canadian Water Resources Journal*
   This special issue includes papers presented at the DRI Evaporation workshop in Saskatoon and includes an overview article by John Pomeroy, Ron Stewart and Rick Lawford.

Other legacy activities include the development and production of a poster on drought, the development of statements on DRI and drought for the Wiki, and a chapter on drought research prepared by Prof. Ronald Stewart for a Canadian version of the introductory atmospheric science textbook *Meteorology Today* by Ahrens. As well, Ronald Stewart and Barrie Bonsal updated the "Prairie drought" section of the online Encyclopedia of Canada.

Recapitulation:

Significant advances have been made in each theme. As outlined in the following theme summaries, progress in Themes 1 and 2 has centred on the deliverables and milestones identified in the original proposal. Progress in Theme 3 incorporated more of the hydrologic prediction activities than envisioned in the original milestones. Contributions have also been made to Themes 4 and 5. Thanks to these advances, DRI and CFCAS are better known by many agencies and groups, especially by water agencies in Western Canada. However, not all the questions regarding Canadian drought, especially future droughts in a changing climate, have been answered and some aspects of drought understanding will only come about when another drought study is fully developed. Some directions for the scientific requirements of a future drought research programme are outlined in Section 5.

3. **Scientific Summaries by Theme:**

3.1. Theme 1 Drought Characterization (John Hanesiak)

Objective

Quantify the physical features of the 1999-2005 drought.

Milestones

- Carry out studies of the signature of the 1999-2005 drought in the water cycle components, including clouds, precipitation, soil moisture, crop yield, snow, runoff, surface water storage and groundwater
- Complete data analysis and documentation of the results
- Assess the methods and indices for monitoring drought
- Data rescue from previous observations and computations of various indices
- Acquire satellite data for the analysis of drought impacts
- Compute energy and water budgets over the Canadian Prairies during the period of drought
- Develop a synthesis of the drought event
- Prepare and submit journal papers

During the first two years of DRI, Theme 1 focused on individual studies of the 1999-2005 drought. A large part of Theme 1 efforts over the past two years has been to develop an overall drought characterization scientific article to appear in the DRI *Atmosphere-Ocean* (*A-O)* special issue. Much of the work in the past two years has been successful in gathering a significant amount of material from DRI Investigators and Collaborators and beginning to synthesize what we have learned. This article was submitted to *A-O* early in 2011. The article highlights many of the key physical aspects of the 1999-2005 drought. It is a multi-authored article (same as those listed below) with Hanesiak (Manitoba) as the lead author.

A summary of the key characterization and synthesis of the 1999-2005 drought is presented here in the form of an excerpt of this December 2010 version of the paper. The text below thus encapsulates the past several years of DRI Theme 1 research as well as the synthesis of this work. The title of the article is "Characterization and synthesis of the 1999-2005 Canadian Prairies drought". The authors are: J.M. Hanesiak, R.E. Stewart, B. Bonsal, P. Harder, R. Lawford, R. Aider, B.D. Amiro, E. Atallah, A.G. Barr, T.A. Black, P. Bullock, J.C. Brimelow, R. Brown, H. Carmichael, C. Derksen, L.B. Flanagan, P. Gauchon, H. Greene, J. Gyakum, W. Henson, T. Hogg, B. Kochtubajda, H. Leighton, C. Lin, Y. Luo , J.H. McCaughey, A. Meinert, A. Shabbar, K. Snelgrove, K. Szeto, A. Trishchenko, G. van der Kamp, S. Wang, L. Wen, E. Wheaton, C. Wielki, Y. Yang, S. Yirdaw, and T. Zha.

The article identified many aspects of the 1999-2005 drought. The area being considered in this analysis is primarily the Prairie agricultural region, although simultaneous impacts were also seen in the southern boreal forest. An analysis was carried out to consider the sequencing of the anomalies in different variables throughout the drought. The compiled anomalies were normalized by dividing the 1999-2005 anomalies by the largest anomaly (+ or -) in the 1999-2005 time frame. Resulting time series variability is no more than -1 to +1, with 0 as the normal of the entire time series.

The variables that were analyzed in this way all varied in terms of spatial representation and normalization period. Negative lapse rate anomalies indicate that lapse rates were greater than average (i.e., more unstable profile) during the drought. Data are for 00 UTC soundings released from Stony Plain, Alberta for June, July and August (JJA) with a normal period of 1999-2009. Precipitable water also came from soundings at Stony Plain, Alberta with a normal period of 1998-2006. Lightning activity was determined from the Canadian Lightning Detection Network (CLDN) for JJA in the boreal and grassland eco-climatic zones with a normal of 1999-2005. Synoptic lows were representative of the southern half of Alberta, Saskatchewan and Manitoba, with a normal period of 1979-2009. Tornado and hail day anomalies were calculated for a normal period of 1985-2007 and were representative of the entire Prairies. Forest evapotranspiration (ET) utilized the Old Aspen ET data, while Grassland ET utilized the Lethbridge ET data; both ET datasets came from Boreal Ecosystem Research and Monitoring Sites (BERMS), with a normal period of 1999-2005. Data for temperature, precipitation, Standardized Precipitation Index (SPI) and Palmer Drought Severity Index (PDSI) came from CANGRID and are representative of the agricultural region of the Prairies with a normal period of 1971-2000. SPI and PDSI were calculated with programmes provided by the University of Nebraska-Lincoln. Wheat yield anomalies (percent from normal) are representative of the agricultural region with the normal period of 1976-2006. Snow depth is representative of the southern Prairie with a normal period of 1979/1980-2003/2004. South Sask (South Saskatchewan River at Medicine Hat) and Assiniboine (Assiniboine River at Headingley) streamflow are representative of the hydrological processes in their basins and utilized normal periods of 1911-2009 and 1913-2009, respectively. Pond count data is representative of the Prairie pothole region and a normal period of 1961-2009. Soil moisture was from the PAMII crop model output for the agricultural region of the Prairies and had a normal period 1998-2005. Total Storage Deficit Index (TDSI) is representative of the Gravity Recovery and Climate Experiment-derived (GRACE) water storage anomaly of the South Saskatchewan River basin with a normal period of 2002-2006.

The drought progressed roughly from west to east across the Prairies and was linked somewhat to the drought that was occurring simultaneously in the United States, as indicated by various datasets (e.g., precipitation, modelled soil moisture, NDVI, PDSI and SPI indices). The aerial precipitation and drought indices information varied systematically over the drought, although there is considerable variation. The years 2001 and 2002 were characterized by the most extreme parts of the drought, with annual precipitation deficits as high as 175 mm to 200 mm (60% to 70% less than normal), with record dry spells across east-central Alberta and west-central Saskatchewan (see Figure 1). Summer experiences the most extreme precipitation deficits when the Prairies typically experience its largest precipitation; however, winter snow cover was below-average throughout the drought as well. In fact, precipitation for the 2000-2001 winter was the lowest on record for the 1960-2005 period. This is consistent with below-normal winter moisture transport over the Prairies from the Pacific Ocean and very little moisture flux convergence over the region, even in summer. Below-normal winter snow cover in 1998-1999 in many areas may have also helped kick-start the drought. The reduced snow cover in spring and lack of summer rain contributed to soil moisture deficits throughout the drought, but was most pronounced in 2001-2002, which in turn was linked to reduced evapotranspiration during the growing season. The previous autumn's precipitation can be critical for the coming spring and summer to act as a soil water storage recharge. Since the Prairies have significant non-contributing hydrological areas, winter can also play a role in spring/summer water stress, with less snow cover to recharge the soil moisture, as was experienced in 2001-2002.

Crops were affected within the growing season and beyond during prolonged below-normal precipitation episodes where reduced snow cover in the previous winter combined with reduced summer precipitation compounded poor crop productivity. The worst crop effects were in 2001-2002 (Figure 1). The southern boreal zone also experienced extreme impacts in some species with the worst effects in 2002 – forests typically respond to drought over one to two years but can recover in a season given sufficient moisture. Stream and river flows were lowest in 2002-2003, towards the end of the drought, although this depended on catchment area) - such factors tend to be cumulative over time and this trend is consistent with the precipitation data. Lake levels respond over various time scales (one to three years), primarily depending on their size and catchment area. The greatest reduction in the number of ponds and the lowest lake levels occurred in 2002, with the greatest groundwater reductions taking place between 2002 and 2004. Groundwater aquifers respond over various time scales (one year to several years), depending on their depth and spatial extent.

Large-scale atmospheric circulation patterns were distinctly different during the drought, with no obvious links to common teleconnections. Teleconnections were such that a moderate to strong La Niña occurred between 1999 and 2002 and switched to weak El Niño conditions in 2003-2004. The PDO and PNA were predominantly negative during the most extreme part of the drought (2001 and 2002) and positive thereafter, while the AMO was in a positive phase throughout the entire period. The lack of both a consistent positive PNA pattern (indicative of enhanced ridging over Western Canada) and a persistent positive PDO during the most extreme drought conditions in 2001 and 2002 differs from teleconnections associated with previous extended dry periods on the Prairies. In addition, no single persistent large-scale circulation pattern existed, although a down-sloping westerly flow and a cooler/drier north-westerly flow were two regimes that dominated between 2001 and 2002; this can be seen in the precipitable water trace in Figure 1. The cooler/drier north-west flow produced a "cold drought" and the persistent omega block pattern (typical of past droughts) did not occur, leading to a general lack of extremely hot days (Figure 1). There was, however, considerable variation within each year.

The dominant circulation patterns reduced precipitable water but made 800 hPa to 500 hPa lapse rates more unstable for most of the drought (Figure 1), with the net result being a reduction in precipitation, although clouds were relatively common in all stages. Concurrently, large-scale low-pressure system occurrences were significantly reduced between 2001 and 2003 compared to the climatological average (Figure 1). Several areas also experienced fewer cold lows between 2001 and 2003; however, some did not. The large-scale flow patterns and lack of low pressure system occurrences may have conspired to reduce lightning, hail and tornado occurrences during 2001 and 2002 (Figure 1), although significant feedbacks with the large, dry surface areas may have also contributed to these reductions via reduced evapotranspiration and moderate above-normal upward sensible heat fluxes. However, extreme precipitation events did occur during various periods of the drought. Over the historical record (as far back as 1960), the incidence of extreme precipitation events during drought increases as the severity of the event increases, particularly for larger extreme events (i.e., daily precipitation greater than 150% of the monthly average precipitation). This suggests that extreme longer-term events such as drought may affect the severity of shorter-term weather events.

The completion of this synthesis represents the fulfilment of the goals for Theme 1. Extensive effort was required to bring together this large and diverse set of data, analysis and model outputs to describe the drought. This effort has provided invaluable experience for addressing future droughts and other hydrometeorological phenomenon.

Given the concern over our changing climate and the probable enhancement of drought, it is crucial that this phenomenon be well understood in order to better anticipate its future occurrence. This synthesis provides a baseline against which climate model simulations can be compared to determine their ability to predict events such as the 1999-2005 drought. Droughts such as the one studied here must be well simulated by models before those same models can be confidently utilized to anticipate future conditions.

In summary, the severe 1999-2005 drought over the Prairies was complex. It illustrated a variable atmospheric environment and a highly migratory and amorphous behaviour at the surface. The concept of a persistent, single environment with constant features did not occur. The research challenge involved an analysis of the various datasets to produce a full coherent understanding (including all of the feedbacks) of drought. Although more research, including model experiments, is clearly needed, this synthesis presents a major advance and highlights the integrated nature of the drought phenomena.

3.2. Theme 2 Summary: Drought Processes (Masaki Hayashi)

Objective

Improve the understanding of the processes and feedbacks governing the formation, evolution, cessation and structure of the drought.

Milestones

- Initiation and continuation of enhanced observation of atmospheric, surface and groundwater processes in research sites
- Data acquisition from collaborating agencies
- Data rescue from previous observations; selection of numerical models
- Initial model evaluations with simple scenarios
- Hypothesis-testing and new hypothesis-generation
- Model sensitivity experiments and further hypothesis-testing
- Completion of data analysis
- Final model runs
- Journal papers submitted

Progress Summary

The following summary is organized according to the spatial scale from continental-scale atmospheric processes to plot-scale hydrological processes. To better understand the water and energy cycling and drought development and in order to assess water and energy budget for the Canadian Prairies, DRI has analyzed processes using observed, remotely-sensed re-analysis and modelled data.

The findings of this Prairie-scale analysis included the following:

- While some of the assessed component budgets for the Prairie water and energy cycle compared quite well with observations, magnitudes of the residuals in balancing the budgets were often comparable to the budget terms themselves in all (re-)analysis datasets, suggesting that substantial improvements to models and observations are needed before we can accurately close the budgets for the region.

- Although evapotranspiration (E) and precipitation (P) dominate the mean warm-season water budgets, the temporal variation of P is strongly correlated with that of the moisture flux convergence (MC) and poorly correlated with E, suggesting that the inter-annual variability of P is strongly governed by moisture transport processes rather than local evaporation.

- Warm-season moisture transport and precipitation on the Prairies are strongly affected by synoptic storm activity, particularly by storms that occur in its southern areas, and by their interactions with topographic features of the region.

- Extreme drought would occur when low winter precipitation, which led to both low spring soil moisture and low evapotranspiration, occurred in conjunction with lower-than-normal frequency of rain-producing synoptic systems during the spring and summer, whereas extremely wet growing seasons are largely a result of an anomalously high occurrence of these systems.

- Both the structure of Prairie extreme rain storms and the dynamic processes that are responsible for their development have been elucidated. Extreme events such as the intense rainstorms that occurred in southern Alberta and Saskatchewan in June of 2002 often alleviate and sometimes initiate the termination of multi-year drought in the region. There is also evidence that conditions during the severe drought contributed to the development of the extreme precipitation system.

- Warm-season synoptic systems provide the critical dynamical link between Prairie precipitation response and large-scale forcings. Hence, the accurate modelling of these systems and their interactions with regional processes and topographic features in the Prairies in models are critical for the improved dynamical prediction of Prairie droughts over different scales.

- The enhanced increasing trends of droughts detected over the western Prairies during the later half of the twentieth century by using PDSI data were not substantiated by trends that were detected by using other datasets (e.g., SPI and assimilated soil moisture).

Many previous droughts in central and Western Canada have been associated with the positive phase of the Pacific North American (PNA) pattern index (i.e., generally anomalous mid- and upper-tropospheric ridging in Western Canada). DRI research has identified a significant trend in the PNA index towards positive values of the past 50 years. Furthermore, precipitation deficits at some locations are not correlated with any of the established teleconnection indices such as the PNA and the El Niño Southern Oscillation (ENSO). An analysis of the different flow regimes that contributed to the length and severity of the recent Prairies drought found that:

- Analysis of jet stream and storm track showed that storm tracks shifted to the north of the Prairie region, resulting in fewer synoptic-scale triggers for precipitation in the Prairies.

- The presence of a meridionally-oriented ridge/trough couplet in western British Columbia shifted the storm track to the south of the Prairies.

- Explosive cyclogenesis in the Gulf of Alaska was observed at the beginning of the 1999-2004 drought.

DRI studies also indicated that the warming trend in the western tropical Pacific and Indian Oceans has a profound impact on the drying regimes on the Prairies. The main findings are:

- Mid-tropospheric circulation patterns that were dominated by anomalous ridging over North America during the warm seasons from 1999-2002.

- The central and western Prairie soil moisture deficit for the 1999-2003 drought period could be linked to the northward extension of wider dry conditions in the western U.S.

- Moderate to strong La Niña during the first part of the drought (1999-2002) that switched to weak El Niño conditions in 2003-2004. The PDO and PNA index were predominately negative during the most extreme part of the drought (2001 and 2002) and positive thereafter, while the AMO was in a positive phase throughout the entire period.

- Moisture from the Gulf of Mexico was notably decreased during the identified drought seasons. Stronger-than-normal subsidence associated with anomalously high pressure over north-western North America also led to weakened moisture transport from the Pacific Ocean. Conversely, during pluvial seasons, low-level flow aided by the circulation associated with increased cyclone frequency over western North America brought abundant moisture northward into the southern Prairie region.

Cloud conditions during drought were compared with those during periods of normal precipitation using satellite data from the months of May to September in 1984-2004 and CANGRID precipitation data. There is a clear trend for months with below-average precipitation to have negative cloud anomalies. However, the value of r^2 is small (0.17); very little of the SPI variation is explained by total cloud amount. Using CANGRID precipitation data on an interpolated grid based on surface observations introduced some uncertainties into the analysis, especially in the northern portions of most provinces where there is less than one station in each 1° × 1° square, particularly in northern Saskatchewan and Manitoba. This means that it is possible for a particular region to be represented by an unrepresentative value of precipitation, just as it is possible for the nearest station to be hundreds of kilometres away and hence provide an unreliable value for the SPI. Uncertainties in the measurements and smoothing of the gridded data may be partly responsible for the weak correlation, but what is probably more important are the contributions of intense but small sub-grid storms that have a greater impact on the grid-averaged precipitation than they do on the grid-average cloud amount or albedo.

We have also conducted an annual and monthly lighting analysis over the entire Prairies between 1999 and 2008. Lightning activity over boreal forest and cropland is seen to decrease as the drought evolves from the beginning to the mature stages and reaches a minimum during the transition stage between 2002 and 2004. Furthermore, as the drought enters the dissipating stage, lightning activity increases. These observations suggest that fewer severe storms might have occurred during the drought. This is consistent with below-normal hail and tornado occurrences/reports observed during the drought. Upon examining convective activity in association with wet/dry areas, we found that less lightning generally occurs over very dry areas but wet areas do not necessarily experience greater lightning. This result supports other findings that sufficient moisture is a necessary but not sufficient condition for deep convection to occur; however, this work explicitly shows the surface's role in the moisture supply. It also proves, for the first time on the Prairie region, that drought perpetuates drought with respect to deep convection.

On a smaller scale, we have examined the flow of atmospheric water through clouds and precipitating systems to the surface within and adjacent to the drought regions, focussing particularly on episodic events. Key findings of this study included the following:

- The 1999-2005 drought was a long way from being cloud-free; cloud fraction was just slightly below normal.
- Virga was common even when locations were experiencing the lowest precipitation on record.
- Record-breaking low precipitation can be linked with a normal number of days experiencing precipitation.

- Major storms can be made more intense by storm-scale interactions with the dry drought environment.
- Cold conditions lead to drought just as effectively as hot conditions.
- Meteorological drought exhibits many types, not just hot, cloud-free and calm; long-lived drought can move between these different types.

Many studies were conducted to understand hydrological processes associated with droughts. For example, detailed field studies were conducted in the West Nose Creek watershed near Calgary to understand how the meteorological forcing factors (e.g., reduced precipitation) affect groundwater during and after droughts. The results indicated that the majority of groundwater recharge occurs under topographic depressions that fill up with snowmelt water because evaporation during the growing seasons uses up essentially all soil moisture on uplands surrounding depressions. Snowmelt runoff generated over the frozen soil is critical for filling depressions and causing subsequent infiltration and recharge. Groundwater level data from the observation well network showed very little spring rise (i.e., recharge) in years with little snowmelt runoff. Groundwater recharge is strongly influenced by the amount and timing of snowmelt, which is dependent on winter weather conditions (e.g., timing and amount of snowfall, occurrence of mid-winter melt). Meteorological conditions in winter and early spring are quite important for determining groundwater responses to drought.

The sensitivity of hydrological processes to drought was assessed using a hydrological model. Prairie spring runoff, soil moisture storage and snowmelt infiltration processes are sensitive to warmer winter air temperatures and decreased precipitation (drought conditions for this simulation) associated with drought conditions. Stubble cover is also a factor in snow accumulation with minimal sensitivity for a single-year drought as decreased snowfall and decreased sublimation balance each other, although multi-year droughts with poor harvests and reduced stubble vegetation height may have reduced snow accumulation in the second and third year. Snow cover duration initially decreased at the beginning of a drought but showed little sensitivity to the onset of severe drought conditions. Soil moisture storage and snowmelt infiltration were affected by drought severity and generally increased as fall soil moisture declined. Winter evaporation increased slightly during drought meteorology but this was more than compensated for by reduced blowing snow sublimation losses. Decreased snowmelt runoff and the associated decline in spring stream discharge in spring were both very sensitive to over-winter drought. In contrast, soil moisture changes had less effect on stream discharge under these dry conditions. In summary, any one of three factors (lower winter precipitation, warmer winter air temperatures or lower fall soil moisture) can cause a dramatic reduction in snowmelt runoff to small streams and sloughs. In addition, dataset development continued for the sites in the National Agri-Environmental Standards Initiative (NAESI) Water Availability project. A Soil Water Equivalent (SWE)/soil moisture mesoscale observation network is being established in collaboration with the Hydrometeorology and Arctic Laboratory (HAL) and the collected data will also be used to support the calibration and validation of the new models. These data are continually being collected and made available upon request. Other datasets include data from an energy flux/meteorological tower and a deep observation well (geological weighing lysimeter).

Analysis of observations at the St. Denis, Saskatchewan site showed that the 1999-2002 drought period was characterized by much lower precipitation, less snow accumulation, shorter snow cover duration, enhanced winter evaporation and much lower discharge to the wetland from snowmelt runoff. As conditions returned to normal, the hydrological conditions remained in a deficit condition even after the meteorological conditions had returned to normal, indicating that hydrological memory tends to lengthen the hydrological drought. This memory arises from:

i) "storage memory" of dry fall soil moisture content which strongly affected spring runoff, and
ii) low water storage in ponds resulting in restricted "fill and spill" from one pond to the next.

Methods for computing evaporation processes were evaluated by a comparative study between the Penman-Monteith (P-M) and the Granger-Gray Dalton Bulk (G-D) Transfer models. These models provided reasonable estimates of evaporation (when compared to observations) on time scales from several days to seasons but gave poor estimates of daily or sub-daily time scales. The P-M method performed the best overall although the (G-D) method provided similar results with fewer parameters. Factors such as heat storage and the spatial variability of surface parameters need to be considered explicitly to resolve the uncertainties in evaporation estimates. A physically-based hydrological model was used to provide a framework for calculations of actual evaporation over the summer period of 2001 at a short grass prairie site located at Lethbridge, Alberta (AMERIFLUX). While both the Penman-Montieth and Granger-Gray models may produce large overestimates of evaporation during a drought period when allowed to run independently, they give reliable estimates when used in a coupled soil moisture-precipitation-runoff water balance approach that constrains evaporation during periods of severe moisture stress.

The spatial variability of evapotranspiration was assessed using radiation data derived from visible and thermal imagery and a single reference value of mean daily net radiation. A new approach has been developed that relies upon distributed estimates of the mean daily net radiation balance and a combination of evaporation models. This approach used the G-D evaporation model to estimate evaporation from a grassed surface at a complex parkland site in central Saskatchewan and demonstrated that the model is a useful and practical alternative to complex evaporation models in data-sparse regions and areas in which detailed soil moisture information may not be available. The technique is amenable to applications using satellite remote sensing information and surface meteorological data. Spatial variations of actual evapotranspiration were estimated for grass surfaces on the Canadian Prairies using the modular CRHM platform during snow and snow-free periods. Actual ET was calculated during the snow-free period by the P-M method and constrained by available soil moisture. While actual ET rates were found to be relatively insensitive to growing season climate when adequate soil moisture is present, these rates decrease dramatically when soil moisture is low. Consequently, there is no consistent spatial pattern in actual ET across the region during the drought period and the patterns of variability shift as the drought intensity increases or diminishes.

Overall, significant progress was made in understanding the atmospheric and hydrological processes and feedbacks at various scales. Models were selected and tested and new hypotheses were generated. Some results have already been published or submitted to journals. Therefore, the milestones for Theme 2 have been largely achieved. Investigators continue to help with the completion of a final hydrological model in conjunction with Theme 3 efforts.

3.3. Theme 3 Drought Prediction (Charles Lin)

Objective

Assess and reduce uncertainties in the prediction of drought and its structure.

Milestones

- Acquire and organize the model outputs and reanalysis datasets to facilitate access and analysis
- Undertake analysis of the archived data to assess model performance and identify the weaknesses in models
- Improve hydrological models to assess drought impacts
- Assess the impacts of initialization data on forecasts of drought-related variables (soil moisture)
- Development of a dynamic drought prediction capability
- Model sensitivity experiments, hypothesis-testing and further hypothesis development
- Final model runs
- Journal papers submitted

We have made significant progress in Theme 3, which is summarized below. A major activity in the final year of the CFCAS grant period has been to contribute to DRI synthesis papers.

- Leighton has continued the comparison of cloud-precipitation relationships from the Canadian Regional Climate Model (CRCM) with those from observations over the Prairies. Different statistics were evaluated, including annual precipitation, cloud cover, top-of-the-atmosphere albedo and SPI index. The CRCM simulates well the average annual, summer and winter precipitation (1961-2004) over the Prairies, but the values of annual precipitation for individual years are not well reproduced.

- Hayashi has improved the evaporation, soil freezing-thawing and snowmelt modules of the Versatile Soil Moisture Budget (VSMB), a groundwater recharge model that is used by DRI partner Alberta Agriculture and Rural Development (AARD). Field data from the West Nose Creek watershed are used and initial development of a three-dimensional groundwater model of this watershed is under way.

- Hanesiak and his colleagues used a multi-model ensemble approach to quantify the uncertainty in modelled ET and root-zone soil moisture. The modelled data are validated against *in situ* observations for three DroughtNet sites in Alberta. The results show that root-zone soil moisture is well simulated. Modelled ET are also verified using two eddy covariance systems over different vegetation types; the difference in ET between contrasting vegetation types is simulated, as is the contrast between wet and dry years.

- Stewart has examined the flow of water through clouds and precipitating systems to the surface in and adjacent to drought regions, with a focus on episodic events that produced heavy widespread precipitation and thresholds for the precipitation to reach the surface. An assessment of how well predictive models capture the flow of water is also under way.

- Woodbury has developed a one-dimensional model based on CLASS that has the capability to simulate groundwater flow. Comparison of this model (gCLASS-1D) to an extensive ten-year dataset from the BOREAS Saskatchewan site has been performed in collaboration with van der Kamp. Snow depth and soil temperature are simulated well.

- Pomeroy has evaluated the evaporation, interception and soil moisture balance modules in the CRHM for application to the Prairie environment. The simulations were carried out over the climate normal period of 1961-1990 as well as the drought period of 1999-2005. Basins are being simulated at multiple scales. Snow accumulation and redistribution, soil moisture, small streamflow discharge and wetland storage have been successfully simulated in the Prairie environment for the first time. The hydrological memory effect of wetlands on drought runoff has been quantified. In particular, the hydrology of the Saskatchewan River Basin is being simulated using a Modélisation Environnementale et Communautaire (MEC) Surface and Hydrology Model (MESH) prototype at a resolution of 15 km and smaller basins with CRHM at a resolution of 1 km. Pomeroy and Pietroniro have also modelled the "fill and spill" of depressions (wetlands) in the landscape. Using current methods, they have produced results that illustrate issues that arise with conventional wetlands "fill and spill" models. Efforts at scaling these algorithms to deal with variable contributing areas in the Prairie pothole regions that dominate much the Western Canadian Prairies are under way.

- Szeto has examined the model bias in the simulation of the 1999-2005 Prairie drought by several regional climate models and model deficiencies have been identified. In collaboration with Aaron Berg, he also performed experiments with the CRCM to investigate the sensitivity of predicted Prairie warm season precipitation to the specification of initial soil moisture.

- Pietroniro and colleagues are improving the MESH model using new coupled modelling formulations with groundwater simulations and results from CRHM simulations. Major improvements include the incorporation of the CRHM's Frozen Soil Infiltration Algorithm into MESH, the alignment of the interflow algorithm with the advanced interflow algorithm from the University of Waterloo and Recherche Prévision Numérique (RPN), and the adaptation of the automated testing system from the Institut National de la Recherche Scientifique (INRS) into MESH.

- Lin has developed a real-time drought monitoring and forecast system based on the macroscale hydrological VIC model over the Canadian Prairies and China. Over the Prairies, daily soil moisture is simulated starting from 1950 and continually running through to the present with a forecast lead time of up to 35 days. The methodology was first developed and tested over the Huaihe River Basin for flood forecasting. An index (Soil Moisture Anomaly Percentage Index; SMAPI) is constructed to indicate the severity of agricultural and hydrological droughts. SMAPI compares well with three other independent drought indicators. A real-time drought monitoring and forecast is now available on the web (www.meteo.mcgill.ca/~leiwen/vic/prairies).

It is also apparent from the foregoing discussion that the drought's complexity poses enormous challenges for its simulation and prediction at all temporal scales using dynamic models. A number of important processes that affect such droughts are generally not represented (e.g. dust's effects on albedo and precipitation production) or only crudely (e.g., surface fluxes from highly variable surfaces) in current climate models. One needs high-resolution models coupled with the surface to address these and many other issues identified in this report. Given the concern over our changing climate and the probable enhancement of drought, it is crucial that this phenomenon be well understood as a key step to better anticipating its future occurrence. Droughts such as the one studied here must be well simulated before one can confidently utilize those same models to anticipate future conditions.

3.4. Theme 4 Summary: Drought History (Barrie Bonsal):

The objective of Theme 4 is to compare "the similarities and differences of the recent drought to previous droughts over this region and those in other regions, in the context of climate variability and change." Although this theme was unfunded by CFCAS, significant progress has been made in comparing the 1999-2005 drought with earlier droughts and, to a lesser extent, with those projected to occur in the future thanks to in-kind contributions from Environment Canada. In addition, Manitoba Hydro provided some early incentives for these discussions because of their interest in knowing whether one or more of the years in the 1999-2005 period should replace 1939-1941, their drought of record for low flows used in planning purposes. Subsequent efforts in developing a synthesis of droughts from the historical record for the paleo record and from climate projections for the next century have provided further motivation for this work.

Barrie Bonsal has led much of the work relating the 1999-2005 drought to atmospheric and oceanic variability associated with previous droughts and pluvials on the Prairies. He identified previous droughts that match or surpass the severity and extent of this drought using both the PDSI and SPI indices. With his colleagues, he has been looking for similarities in formation, migration and termination of some of these drought years including 1929, 1931, 1936, 1961 and 1988. They have applied a six-stage framework for drought events and examined how each drought progressed in comparison to the DRI focus drought. Other studies included an extended analysis of historical severe weather (hail and tornadoes); lightning and cold low datasets by John Hanesiak and his colleagues; a study by Lisa Hryciw on droughts across Canada between 1948 and 2005; and a study of the relationship between precipitation and clouds over the Prairies for the 20-year period (1984 to 2004) using data from the International Satellite Cloud Climatology Project (ISCCP) Saskatchewan River Basin (SRB) datasets.

Another study has correlated the values of seasonal teleconnection indices of the SOI, PDO, PNA, AMO, AO and NAO with drought indices over the Canadian Prairies (SPI, PDSI, PDSI Z-value) at various lag and lead times for the entire instrumental period of record. Significant relationships exist between the drought indices and individual teleconnections, such as the PDO and PNA. While DRI has not provided dynamic prediction systems, through this work it has contributed to improved probabilistic assessments of the occurrence of droughts. Well data observations have been compiled and analyzed for the period 1965-2005. Lake level data from 1910-2007 helped establish a basis for comparing the effects of the recent drought with previous droughts.

Using non-linear mathematics to examine the drought events' hydrometeorological extremes in historical time series of temperature and precipitation from high-quality datasets of more than 100 years in duration, DRI has found that these extremes are weakly multi-fractal over periods shorter than one month. This is a feature that controls their scaling properties and can be used to statistically disaggregate monthly data to shorter-duration values. Furthermore, temperature and precipitation datasets are very different in their behaviour. Temperature datasets are non-stationary and have multi-fractal properties which show little change over the recorded period. Precipitation data appear to be more stationary, but their multi-fractality shows much greater temporal variability.

Even in the absence of funding, Theme 4 made some advances thanks to the commitment of several DRI Investigators and Collaborators. Its greatest achievement is anticipated to be the completion and publication of the synthesis paper that will be produced at the end of DRI.

3.5. Theme 5 Drought Response (Elaine Wheaton)

Theme 5 was another unfunded activity which called on DRI Investigators to provide advice on how to use the results to mitigate the impacts of drought in the future. DRI supported this theme in a broad way through its Partners Advisory Committee, which enabled Stakeholders and user communities to have more input into DRI management. Through a successful proposal to CFCAS, DRI obtained resources to develop drought simulation exercises that came to be known as DEWS. The DEWS exercises were held in each Prairie Province and provided a useful tool for engaging users in discussions about DRI outputs. In addition, support was provided from the central DRI budget for user workshops as part of the overall outreach for the project.

Specific DRI projects have produced results that support the goals of Theme 5. Many of the published studies document some aspect of the extent of the drought, including assessments of the drought on the hydrology of the South Saskatchewan River basin and with water use in the South Saskatchewan River basin. As noted in this report, one DRI Investigator has worked closely with municipal authorities to establish a groundwater monitoring network that will provide baseline data for assessing and responding to future droughts.

Many of the DRI researchers work with partners; these linkages benefit each partner's work and collectively benefits society. Information on drought is useful to the design of sustainable resource management strategies and the development of drought warning strategies. For example, the CRHM's research will provide information for sustainable water management and provide assessments of the impacts of climate change scenarios. Another example is the improved understanding of groundwater resource dynamics, which benefits the many users of this vital resource. One DRI Investigator has assisted in designing a groundwater monitoring network at the county level and is providing advice to the Alberta government on ways to improve a model that is being used in a forage crop insurance programme.

The expertise developed by DRI scientists through their research has led to recognition by the community. For example, Paul Bullock, Elaine Wheaton and Rick Lawford participated in meetings on various federal and provincial initiatives on agricultural adaptation strategies. Other user interactions arose from several other University of Manitoba studies involving estimates of surface evapotranspiration, assessments of irrigation demand and simulations of streamflow over the Churchill River Basin in Manitoba. User workshops were held in each of the three Prairie Provinces during the past year. These workshops indicated that users were beginning to find DRI results useful and were benefiting from the insights emerging from DRI research.

As noted earlier, Professor Stewart is holding a lecture series as part of DRI outreach activities. While most of these lectures are being given to university students and faculty, they have all attracted many members of the general public. In each case, questions asked by audience members have indicated that the public is very interested in this issue, underlining the point that DRI has contributed to addressing this need.

3.6 Follow-on Science

Outstanding scientific questions that need to be addressed in future drought studies.

While DRI made substantial progress in understanding drought, it has not fully addressed the problem of predicting drought or putting this drought in the context of historical droughts or droughts in other locations. This arises from the need for a better understanding of certain drought processes and to incorporate these processes into models. A compilation of the views of important problems led to the following insights.

In terms of modelling drought processes, there is a need to examine cloud and precipitation parameterizations in the CRCM and other atmospheric models. If these parameters are inadequate, the energy and water cycles could become decoupled. Another area in which models need improvements includes assessment of their ability to represent the large-scale and regional factors that affect the variability of warm season continental synoptic storm activities. These factors need to be identified and better understood. How well these processes are captured in current models also needs to be assessed. For example, mesoscale model runs could simulate the role of dry air over drought regions in providing lifting for moisture and thunderstorm initiation on the downwind side of the drought regions. They could also simulate how urban dry islands downwind of larger Prairie cities affect storm systems, precipitation, and possibly their role in enhancing existing downwind drought regions.
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Another set of processes involved the remote forcings on a global scale that are transmitted by the atmospheric circulation. This could be addressed by comparing the 1999-2005 drought with other drought events to assess why the large-scale factors and teleconnections associated with this drought differed from those associated with previous Prairie droughts and what implications these differences have for understanding and predicting future drought occurrences in this region and other regions of Canada and North America. In particular, we need to focus on the generation and decay phases of droughts, with a particular emphasis on the blocking

phenomenon. In addition, the role of the air-sea fluxes in the North Pacific in initiating atmospheric teleconnection patterns over the Prairies needs to be better understood.

DRI studied the drought using data products, model outputs and data assimilation products. The current datasets were limited in the degree to which they quantified and clarified the relative roles of soil moisture, evapotranspiration and atmospheric circulations and associated moisture transport in affecting Prairie precipitation, and how they might change over the growing season. For this reason, Prairie water and energy budgets and their closure need to be reassessed on an ongoing basis when new reanalysis, observations and improved models become available.

From a hydrologic perspective, DRI was well timed to observe the recovery of groundwater from drought conditions. Using the research infrastructure established during DRI, this research community will be able to conduct detailed observation of groundwater during the entire period of the next drought, including its beginning. More generally, drought impacts on water resources need to be simulated over the major river basins using physically-based and hydrologically correct models. This is crucial in order to determine the resilience of water apportionment agreements during drought.

The connections between drought events need to be understood. The continuation of drought can be a mystery because these persistent, low-precipitation conditions were maintained in spite of large-scale forcing changes. A number of different chains of events are responsible for entering and maintaining drought or for exiting a drought. Often these chains of events include severe droughts and extreme precipitation events following each other in quick succession for no well-understood reason. These processes need to be studied on both a statistical and physical basis. Furthermore, there is a need to understand the degree to which these issues are universal and the extent to which the results of this study can be extended to other regions. The process of warm season orographically-induced convective precipitation needs to be better understood.

Looking to the future, trends of drought on the Canadian Prairies should be the priority in drought studies. This is especially relevant for adapting to a changing climate. Furthermore, we must be able to assess how the regional feedback processes and warm-season synoptic storm activities might change in a warmed Prairie environment and their subsequent effects on future precipitation in the region. Drought monitoring must also be strengthened. Effort must be directed at developing advanced indices and other methods to improve understanding and characterization of droughts.

The data that has been generated through DRI also needs to be exploited. The daily runoff depths at each of the 4,393 modeling points from VIC over the Prairies are potentially useful for Prairie water resources studies. Hydrographs simulated at different cross-sections on the Prairie river system could be used for flow forecasting.

4.0 DRI Impacts

4.1 Contributions of DRI to the Initiative's overall objectives and our scientific understanding of drought.

At their highest level, the targets for drought research are:

- To better predict droughts over Canada, their detailed structure and their impacts with increasing confidence; and
- To better assess whether there will be a "drying of the continental interior" in the future.

In order to scope out a project that could serve as the first contribution to these broad goals, the objectives for DRI are "to better understand the physical characteristics of and processes influencing Canadian Prairie droughts, and to contribute to their better prediction, through a focus on the recent severe drought of 1999 - 2004/05." It is accurate to say that DRI has made significant progress towards addressing its objectives, although a decade or two of additional research would likely to be needed to fully address the broad targets of drought research. As noted earlier in this report, the scope of the DRI phase of drought studies had set the following goals:

- quantify the physical features of this recent drought;
- improve the understanding of the processes and feedbacks governing the formation, evolution, cessation and structure of the drought;
- assess and reduce uncertainties in the prediction of drought and its structure;
- compare the similarities and differences of the recent drought to previous droughts over this region and others in the context of climate variability and change; and
- apply our progress to provide advice on how to mitigate the impacts of drought in the future.

The following paragraphs give a short assessment of the achievements of the goals on a case-by-case basis:

Goal #1: Quantify the physical features of this recent drought.
The recent drought met all of the general criteria for a meteorological drought, an agricultural drought and a hydrological drought at certain times in a number of regions.

Drought Synthesis:

A number of investigations were directed at quantifying the physical features of the drought, including studies that evaluated methods for monitoring drought and drought impacts and the development of a synthesis that showed the interactions between the various factors as the drought matured. The production of a synthesis of the factors that tracked the drought's intensity is a major contribution of this study. The synthesis, led by John Hanesiak and Ron Stewart, included the assessment of methods for monitoring drought. They have produced more analysis to complete the integrated assessments of drought characteristics and the imminent publication of the synthesis and fulfilling the first objective of the study.

Meteorological Droughts:

DRI has developed new insights to expand our understanding of drought. One key insight is that meteorological drought has different "types." The traditional concept that all droughts are linked with clear skies and high temperatures has been challenged by the drought of 1999-2005. This event showed that droughts sometimes occur under cold conditions, are windy and dusty, may be linked to no precipitation at all or interspersed with light events or, on occasion, torrential precipitation. Knowledge of the likely "type" of meteorological drought is an important step in recognizing the requirements for drought prediction and drought adaptation.

A water and energy budget study quantifying the physical features of the 1999-2005 drought examined the interplay between the different processes governing the variability and extremes of Prairie precipitation. Using new datasets and indices, we were able to create tables and figures to explore areas of drought research (e.g., the six-stage drought system). These developments have bettered our understanding of drought characteristics such as duration, frequency, severity and geographic extent and pattern.

Agricultural Droughts:

DRI, through the efforts of Paul Bullock, demonstrated that for agricultural droughts derived agrometeorological parameters (evapotranspiration) provide a more accurate characterization of crop response to drought than climatological variables or indices such as the SPI. He also demonstrated that Moderate Resolution Imaging Spectroradiometer (MODIS) images can provide an accurate indication of crop yield on the Prairies prior to the harvest of the crop and thus provide useful information for drought preparedness planning.

Water Resources:

On the hydrological side, a hydrological drought sequence was proposed to help classify hydrological droughts. This sequence lags meteorological drought due to soil moisture and snow accumulation controlling field scale runoff generation and wetland storage of runoff controlling small basin discharge generation. Discharge from small basins is not completely attenuated until wetland water storage, soil moisture and snowpack are all at low levels. In addition, insights were gained regarding the use of runoff and the frequency analysis of discharge data as an index for drought monitoring.

Goal #2: Improve the understanding of the processes and feedbacks governing the formation, evolution, cessation and structure of the drought.

Studies addressing this theme and goal identified a number of important processes that are not adequately represented in models. DRI studied the linkages between soil moisture, NDVI, convective activity and lightning and documented the relationship between lightning events and areas in which no precipitation and dry vegetation prevail. The relationship between cloud anomalies and precipitation anomalies were explored for the different stages of drought. These relationships provide constraints on models that are being used to simulate and hence improve understanding of the processes and situations that favour sustained drought. Comparisons between observations and results from numerical simulations showed a significantly strong relationship between SPI and cloud amount than was present in the observations.

Studies of the large-scale atmospheric circulation and ocean surface temperatures provided insights regarding the relationships between large-scale atmospheric circulation patterns and teleconnections during various drought phases. The research also has implications for assessing and reducing uncertainties in the prediction of future droughts through an application of new understanding of the large-scale causes of drought gained from DRI research. These analyses have also provided an enhanced understanding of the role of synoptic-scale modulation of the drought process.

Hydrological process studies show that spring runoff and streamflow discharge are inherently unstable in the Canadian prairie environment and so magnify the effects of changes in weather patterns typical of drought. This provides an understanding of the rapid depletion of water storage in prairie streams, sloughs and wetlands during drought; in essence, the relatively small moderation of Prairie winters during droughts dries the Prairies out.

Research showed that the processes governing hydrological drought, which included groundwater, have a longer response to the meteorological drought, accounting for the lag between surface and groundwaters both in the onset and termination of the drought. In addition to precipitation inputs, many other factors influence groundwater recharge, including snowmelt runoff, which accumulates in landscape depressions. These processes have been captured in a groundwater recharge model that provides an essential link between meteorological forcings and groundwater response, thereby improving our understanding of groundwater during and after droughts. The connection between surface hydrological processes and wetlands in delaying hydrological response to meteorological drought has been quantified for the Prairies.

Issues such as marginal precipitation occurrence and individual storm events have been examined in this study. Virga (precipitation that was produced aloft but did not quite reach the surface) was very common during the drought. It was also shown that dry drought conditions can, under the right conditions, actually enhance a storm and lead to more precipitation because the dry environment and the storm can interact. These results are important broadly because they could impose new, more stringent requirements for performance by climate models. Other exploratory findings that could have far-reaching effects are the dryline/thunderstorm, drought/thunderstorm and urban dry island work (Edmonton and other transects) results, all relevant to drought enhancement.

Goal #3: Assess and reduce uncertainties in the prediction of drought and its structure.
Work related to the reduction of uncertainties in predicting drought progressed on two fronts. A physical approach involves linking all the physics of water cycle processes by properly coupling the atmosphere, land surface and groundwater components. DRI developed numerical methods by modifying and implementing the multi-layer version of gCLASS with its user-friendly input/output, which was welcomed by users of the model. Only a few researchers are on this critical path, which indicates that DRI has advanced this modern hydrological coupling trend with more powerful numerical and optimization tools. The use of the Soil Atmosphere Boundary, Accurate Evaluations of Heat and Water (SABAE-HW) model, refined through these studies, is used by Canadian students, trainees and engineers to assess the effect of climate on soil moisture, temperature, freezing and thawing.

Based on field studies and fine-scale modelling studies, a comprehensive hydrological model (CRHM) has been developed. It contains physically-based blowing snow, snowmelt, infiltration to frozen soils, infiltration to non-frozen soils, evapotranspiration, wetland storage and runoff components. It has been applied across the Prairie region during drought and non-drought periods to evaluate the regional differences in the effects of drought on hydrology and the temporal pattern of hydrological drought. This is the first known calculation of small basin streamflow across the Prairies using a physically-based model and the first Prairie-wide simulation of evapotranspiration that takes into account the full hydrological inputs to soil moisture. It is the first comprehensive description of local-scale hydrological drought across the Canadian Prairies.

Soil moisture is a critical variable in monitoring drought. Soil moisture is of direct interest to agricultural operations and is linked to the atmosphere through precipitation and evapotranspiration. It is difficult to obtain soil moisture measurements from field surveys on large scales. There is no consistent soil moisture monitoring networks that can provide long datasets of soil moisture conditions in Canada. The development and modification of macroscale surface and groundwater hydrological models has provided the potential to reconstruct and continually update spatial and temporal distribution of soil moistures over a large area. The modified VIC model has been producing historical and forecast products.

Model intercomparisons conducted in DRI have been helpful in quantifying uncertainties and focusing model improvement efforts. Results from the inter-model comparison study and CRCM sensitivity study as well as the enhanced understanding of processes that govern drought development in the region contribute to DRI's objective of assessing and reducing the uncertainties in drought prediction.

Goal #4: Compare the similarities and differences of the recent drought to previous droughts over this region and others in the context of climate variability and change.

Studies of large-scale circulation patterns, synoptic-scale processes and the spatial distribution of drought indices and their relationship to the planetary flow have enabled a comparison of similarities and differences of the recent drought to previous droughts (and even pluvials) over the Canadian Prairies for the period with instrumental records.

Goal #5: Apply our progress to provide advice on how to mitigate the impacts of drought in the future.

DRI Data Management has contributed extensively to each of DRI's objectives. The science is based on data, and the organization of the data within the network for research as well as in the data legacy for public access has facilitated the scientific progress and sets a foundation for future research to carry forward.

In summary, most of the short-, medium- and longer-term DRI objectives have been achieved. A number of deliverables have been produced, including the initiation of synthesis projects related to drought processes in the 1999-2005 drought; the characterization of drought and drought prediction; the drought data legacy; and preparation of other DRI publication legacies, including a special *A-O* issue and the DRI Professional Document.

4.2. **Contributions to government policy:**

DRI influences on policy have come in a number of ways. These influences range from recommendations and improvements to advisory services and the introduction of DRI scientists to other fora where policy is discussed. It is anticipated that the results of DRI in general will contribute to future government policy development regarding the occurrence and causes of hydroclimatological extremes both in the Prairies and throughout the rest of Canada. Concepts such as the different types of meteorological drought, with varying features and impacts, may contribute to this range of policies.

One of the most innovative contributions of DRI to policy development came through its collaborations with AAFC through the DPP and DEWS exercises. DPP workshops were held in Manitoba and Saskatchewan, while DEWS workshops were held in all three Prairie Provinces. The DPP project assessed the ways in which formal institutions respond to and plan for drought in order to gain insights into possible drought preparedness augmentation strategies. A major component of the DPP is to move institutions away from their typical disaster management approach during drought and to create pathways for institutionalizing a risk management approach. Proactive impact mitigation planning to minimize risk is fundamental to the risk management approach but overlooked in the disaster management approach. Within the DPP framework, DRI and AAFC explored the value of information in the drought preparedness process, how it is used, and how its use could be improved. Since we anticipate more frequent and severe droughts that are likely to require proactive management, institutionalized drought-related risk management and improved information could go a long way in preparing institutions for future drought conditions.

DPP and DEWS used simulations of past droughts, especially the 2001-2002 Canadian Prairies drought, to seek answers to the following questions: how can institutions address past weaknesses in their drought preparedness? How can information be enhanced, in terms of quality, timeliness, and accessibility, to increase drought preparedness? In these simulations, participants were led through a simulation of a past drought and were invited to discuss their institutions' responses, or lack thereof. Drought preparedness was characterized qualitatively through discussion and quantitatively, in terms of the pre-2001-2002 drought, with a questionnaire. Participants were then moved through a hypothetical future drought scenario and were asked how their institutions might respond, how future responses could be improved, and what immediate actions can be taken to mitigate future drought impacts and increase preparedness. Following the future scenario, a more in-depth investigation of the role of new information in drought preparedness was conducted through the DEWS simulation.

Analysis of the results indicated that participants perceived that overall provincial drought preparedness improved when compared to its status before the 2001-2002 drought. Major improvements occurred in terms of the availability, quality, and timeliness of information. Resources, on the other hand, in terms of budget and staffing, were perceived as contributing less to drought preparedness in more recent droughts. The preliminary conclusions of the DEWS exercise are that the greatest barrier for the use of drought information involves the proper understanding and use of data. The exercise led to a number of recommendations to improve policy development in areas that support drought planning and advance resource allocation for drought impact mitigation.

A very innovative policy-related development that grew out of DRI and the DPP/DEWS activities has been the Drought Tournament designed by AAFC staff in consultation with DRI scientists. The design of this tournament was led by Dr. Harvey Hill and his colleagues. They worked with Dr. David Sauchyn, a DRI Collaborator, to develop a multi-year drought scenario derived from paleoclimatology data but clothed with details of modern-day impacts derived for DRI and related studies. The purpose of this simulation is to engage people from different sectors and backgrounds in the discussion of policies to deal with drought impacts. A major step in the development of this policy tool occurred in Calgary in February 2011 when five teams, four referees and seven observers participated in the first drought tournament. The interaction of drought experts and water managers facilitated by these simulation exercises has many benefits. One social scientist observed that his collaboration with DRI scientists had increased his credibility when interacting with policy specialists.

Drought monitoring is normally performed using drought indices to provide decision-makers with information on drought severity. In some cases, drought indices can be used to trigger drought contingency plans and financial support programs, if they are available. Plant moisture demand (i.e., potential evapotranspiration) has been shown to be more strongly related to wheat yield and quality than precipitation or other precipitation-related drought indices. Therefore, improved accuracy of meteorologically-based agricultural drought indices can be achieved based on these methods. More accurate characterizations of agricultural drought will help improve various provincial and federal agencies' response to drought by providing more accurate information on the extent and intensity of agricultural drought. This will facilitate a more appropriate level of response to drought and will help ensure that programme payments are targeted effectively to assist those most in need.

DRI models have provided insights into the movement of surface waters. The results are being used to develop local and provincial wetland conservation strategies in Saskatchewan, Alberta and Manitoba in light of variability due to drainage and drought. Techniques for groundwater monitoring and the evaluation of the effects of drought and pumping on groundwater levels have been adopted at the regional level the County of Rocky View in Alberta.

As a result of their research, several DRI scientists have been invited to participate in a number of science and policy discussions, including a multi-provincial/state initiative on the development of agricultural adaptation strategies for climate change in the Northern Great Plains of North America.

A series of user workshops were held in each Prairie Province to explore the benefits and uses of DRI research in policy work and in the work of provincial and federal departments. In addition to the successes reported here, users identified additional work that could be undertaken in order to further benefit their activities. A future drought research programme may be able to address these issues.

4.3. **Expanded contacts in partner organizations.**

The DRI project has expanded contacts for the drought research community as a whole as well as for individual Investigators. Many of these collaborations involve DRI projects and "DRI Spin-off" projects. The results of the DRI project have generated interest and financial support from the Canadian Wheat Board, Manitoba Water Stewardship, Manitoba Agriculture, Food and Rural Initiatives and Manitoba's Agricultural Research Development Initiative to develop a system to generate real-time modelled values of soil moisture for the Prairies using an expanding network of real-time weather stations for data input.

Also, as a result of DRI outreach, the research community has built the following collaborations:

- Research collaborations between government (e.g., Environment Canada) and university scientists; transfer of technology between the institutes (e.g., the enhanced awareness of Environment Canada-developed datasets and their utilizations by university scientists in drought research) have been enhanced substantially through work performed in DRI.

- DRI has enhanced collaborations between the Saskatchewan Research Council and the Canadian Forest Service, the University of Manitoba and Environment Canada.

- New contacts were forged between DRI Investigators and Ducks Unlimited, the Prairie Habitat Joint Venture Policy Committee and the provincial governments of Saskatchewan, Alberta and Manitoba.

- Contacts and collaborations were developed between an Alberta DRI Investigator and Alberta Agriculture and the Rocky View municipality.

- McGill University is continuing collaborations with the University of Calgary on the processing of GPS data, an effort that promises to enhance our understanding of sub-synoptic evapotranspiration processes in regions prone to droughts.

- Individual DRI Investigators have established new linkages with fellow researchers in other disciplines such as agriculture, water resource management and disaster management, especially within provincial agencies.

The Data Legacy work and DRI contributions to GEO through links to its "Impacts of drought" sub task (Task WA-06-02b) has strengthened Canada's contributions to GEO and has led to the interaction between GEO experts and DRI scientists. This was facilitated through the GEO-DRI workshop, held in Winnipeg in May 2010. A spin-off has been the inclusion of the DRI Data Legacy as a decision-support application (in response to a June 2009 call for proposals benefiting societal benefit areas (Water, Agriculture, Weather and Climate) that are of importance to GEO.

4.4. **Enhancement or improvement of the reliability of predictive methods:**

DRI has led to an increased understanding of drought occurrences' causes and scale, which will aid in the better prediction of these events once this improved understanding is incorporated into global and regional scale coupled land-atmosphere models. DRI's scientific contributions came about by developing process understanding and representations that can be included in models and providing evaluation data against which models can be compared.

In particular, hydrological models such as CRHM have been improved as a result of DRI such that they can predict Prairie hydrology from small basins. For example, the SABAE-HW model was benchmarked using actual atmospheric and soil data from DRI. Contrasting solutions computed by the three codes (evaporation, water pond, snow depth, moisture, temperature and so on) show that SABAE-HW provides more accurate predictions than the original version of CLASS (2.6) that was assessed.

DRI results have set standards that predictive methods and models must attain. Current models, for example, generally do not handle virga very well, although this was an important phenomenon during the 1999-2005 drought. In addition, the identification and characterization of a cold drought, with the attendant large-scale forcings distinct from "hot" drought, can be utilized in empirical approaches to drought prediction. In addition, work on the historical analysis of droughts through assessments of sea surface temperatures and large scale atmospheric circulation patterns and has provided a basis for probabilistic assessments of the occurrence of droughts.

Through the work of Charles Lin and Lei Wen, DRI has systematically reconstructed a 60-year record of daily soil moisture conditions and deterministically forecast droughts with a lead time of up to 35 days for the entire Prairie Provinces using the marcoscale VIC hydrology model. This VIC Prairie soil moisture simulation is updated daily and the SMAPI results are publicly accessible online. These maps have already attracted visitors from cross-disciplinary sectors in both Canada and China.

Alain Pietroniro and colleagues continue to develop the MEC/MESH model and its links to Numerical Weather Prediction through RPN in Dorval, Quebec. By developing and using software engineering processes, significant progress has been made in interacting with other modelling groups. An accessible software configuration management (SCM) system for effectively working with code developers and modellers across the country has been developed. Other advances in the implementation of software engineering include improved documentation and the beginning of regular code reviews of MESH subroutines.

4.5. The impact of DRI on local institutions:

A number of universities involved in DRI have been able to increase the number of graduate students in Meteorology and Hydrology departments by enriching their course offerings and enhancing the visibility of their universities in areas of interest to students. Extremes such as drought are very important in the public's eye and the public recognizes that there is great value in understanding them more fully. The subject of drought has attracted students interested in both climate and hydrology, and research funding from DRI has provided support for them as they undertake their research. Furthermore, DRI research funding has led to a large number of publications on topics that have enhanced the profile of DRI Investigators and increased their influence through their contributions to operational services and policy discussions. Specific evidence of the benefits have included the strengthening of the University of Saskatchewan's Centre for Hydrology, its collaboration with NHRC and its successful bid for a Canada Excellence Research Chair (CERC) in Water Security with a research focus on hydrology.

Within government, DRI facilitated or strengthened research collaborations among scientists from different divisions within Environment Canada (EC) to work on a focused subject that is relevant to the Departmental mandates. MESH testing under DRI will form the basis for improved operational land-surface modelling within the context of both the EC NWP model and the CRCM. It also increased Environment Canada and Saskatchewan Research Council interactions to document the extreme hydrologic events and their impacts on the hydrology and ecology of Saskatchewan and of Canada.

DRI workshops provided the framework for pan-university contacts and new partnerships. For example, Woodbury, Hanesiak, Akinremi and Buyian collaborated on a study of Ground Surface Temperatures (GST) as part of their climate change research. The results showed that latent energy effects will be important for interpreting climate change effects and seasonal biases in GST reconstructions from borehole surveys.

4.6. Contribution to a broadened support base and new partnerships;

The DRI project helped several Investigators acquire funding for special studies. For example, DRI research was leveraged in Alberta to secure \$500,000 for a project on groundwater sustainability in the County of Rocky View. Studies in Saskatchewan also obtained funding from SWA, MWS, PFRA, DUC and PPWB based on leveraging through DRI. One Investigator at the University of Manitoba obtained partial support for a Ph.D. student for a project titled "Water Sustainability under Climate Change and Increasing Demand: a One-Water Approach at the Watershed Scale". More details on the other sources of funding for DRI projects can be found in Table 3.1.

One DRI Investigator (Woodbury) received funding from the CWN to carry out work that compliments the DRI initiative with Professors Hendry, Parkin and Thomson. This CWN work will extend that application of DRI results in a cross-disciplinary framework with Engineering and Applied Sciences (Memorial University of Newfoundland), Geology (University of Calgary) and Biosystems Engineering (University of Manitoba).

4.7. Links with international initiatives:

DRI has allowed for strong linkages with the World Climate Research Programme (WCRP) and the Global Energy and Water Cycle Experiment (GEWEX) in particular. DRI was, to some degree, a forerunner in terms of comprehensive research activities examining extremes such as drought. The whole issue of extremes, including drought, is now very high on the agenda of several international organizations. DRI has contributed significantly to the planning of studies of extremes in the international climate community.

The results also promote the concepts of sustainable development, which are being applied internationally through the Commission on Sustainable Development. DRI has had many socio-economic and environmental applications, some of which are documented in DRI publications. These applications relate mostly to the vulnerability and adaptability of rural communities to water scarcity and climate change.

As noted earlier, DRI has contributed to specific international initiatives. It is a Canadian contribution to the International Decade for Prediction in Ungauged Basins (PUB) of IAHS (IUGG). Some of the results of DRI have contributed to international GEWEX Extremes and RHP initiatives. DRI has contributed to GEO activities through the "Impacts of drought" sub task (Task WA-06-02b) and the inclusion of the DRI Data Legacy as a decision-support application in the User Interface Committee/Capacity Building Committee June 2009 call for participation.

The DRI project also contributed to the plans for the Integrated Research on Disaster Risk (IRDR) by gathering the Climate Extremes community together to discuss the needs for research and services related to climate disasters. IRDR is a new programme under ICSU and ISSC, among others, which studies ways to characterize hazards, vulnerability and risk; to promote effective decision-making in complex and changing risk contexts; and to reduce risk and curb losses through knowledge-based actions, areas in which DRI has made contributions in terms of drought. Two workshops, either sponsored (February 2011) or co-organized by DRI (June 2009), allowed DRI scientists to present their work to a larger community interested in disasters.

Some DRI Investigators have been able to arrange exchanges of research associates and students from other countries related to DRI studies. For example, a visiting scientist took part in some of the research in 2009 and provided a valuable contact to the Rubber Research Institute in Kerala, India.

4.8. Commercial or social application of the results:

In terms of specific commercial developments, there appear to be limited commercial opportunities at present since the knowledge arising from DRI projects is embedded in understanding and models. Improved agricultural drought monitoring, prediction and assessment helps all Canadians by ensuring better allocation of public funds in situations where severe drought results in government support. The project may indirectly lead to improvements in the ability to predict drought by forcing those developing the simulation models (CRCM specifically) to examine cloud and precipitation parameterizations.

4.9. Anticipated benefits for Canadians:

Inevitably, the largest benefit of the DRI project will be the highly skilled professionals and researchers that have been trained as a result of DRI and have now entered or soon will be entering the work force.

Although not in a direct manner, this work will advance our understanding of the extreme events that impact Canadians. DRI research results will be a source of advice for improved management of water resources, including groundwater, during periods of water stress. This is particularly true for applications of drought mitigation activities for improved farm- and community-scale water supply estimates.

Drought is a major issue in Western Canada. Better understanding of its fundamentals can be applied to improved monitoring, prediction and adaptation. We are just beginning to explore benefits, which include implications for water management and community vulnerability. Through this project we hope to better identify the early warning signs of drought and other stages of the drought in order to reduce community vulnerability, particularly in periods when droughts are more frequent.

Many of the benefits of this research will not translate immediately into improvements but they will contribute to them in the future. These benefits, which include the improved understanding and prediction of drought and other hydrometeorological extremes on the Prairies, will be felt in agricultural activities, sustained economic and societal developments and planning and the general well-being of Canadians living in the region and beyond.

4.10. Reverse Impact Statement (What would have happened in terms of the project, the resulting science and the impacts on users/stakeholders, if the work had not been funded by CFCAS.)

Without exception, DRI Investigators indicate how critical CFCAS support was for their research. In essence, very little of this research would have been undertaken and what research would have been done would have been carried out as individual or small group efforts with a different emphasis. The synthesis of all of the findings for the drought of 1999-2005 would have been impossible to achieve without the collaborative effort generated by DRI. The students listed in Table 7.1 as well as those who obtained other development opportunities would not have had those experiences and opportunities if DRI had not been funded. Furthermore, the theses and journal papers written as a result of DRI would not have been produced.

The synthesis provided by DRI allowed research conducted by individuals to be integrated with the understanding of studies on other scales. DRI allowed for more intercomparisons and integration because it involved a number of studies done in the framework of the same event in the same region during the same time period. This integration was vital to obtaining a better understanding of critical hydroclimatic extreme events such as droughts from numerous research, operational and stakeholder perspectives.

In terms of our knowledge base, we would not have come to an early understanding of the role of global Sea Surface Temperatures (SST) in initiating and maintaining protracted droughts on the Prairies, nor would we have understood the role of “large-scale factors associated with drought”.

There would have been broader impacts in terms of the linkages with local communities. Without CFCAS funding, the West Nose Creek study would have been discontinued, resulting in lost opportunities for: 1) understanding groundwater recharge processes; 2) development and introduction of the locally-based monitoring in the county; and 3) improvement of the Versatile Soil Moisture Budget model.

Benefits are already flowing, however. Without this research, the following would not have occurred:

- The concept of utilizing “consecutive dry days” as an indication of drought occurrence is insufficient. The recent 1999-2005 drought generally had as many days as normal with precipitation and yet it produced major drought impacts. This limitation is now being recognized by some of the statisticians concerned with extremes and climate.

- The realization that models poorly handle virga and that this is an important shortcoming is being better recognized. The European Centre for Medium-Range Weather Forecasting (ECMWF), for example, is now more fully aware of this issue and recognizes its models' weakened ability to handle it.

- The concept that severe drought and severe storms can interact and, in doing so, may actually intensify the storms. This interaction between dry and wet areas accounts for the highly variable summer climate on the Canadian Prairies.

If DRI data management had not been funded by CFCAS, data collection, management and dissemination during the project would not have been centralized, leading to inefficiencies, replication of effort and limited access to computationally demanding datasets. The DRI Data Legacy, which is a crucial summary and dissemination of the entire network's work, would not exist without this support. Future drought science in Western Canada would not benefit from CFCAS' investments in DRI if the data utilized was not archived publicly; future drought research efforts would have to start from square one in terms of data.

Without DRI, Canada would have been unable to benefit from a unique study of one of its largest natural disasters. This study has led the way for hydrometeorological programmes around the world. Without CFCAS funding and DRI, we would not have a comprehensive understanding of Canadian Prairie hydrology, nor would we have a working hydrological model that can describe the hydrology of small Prairie basins. We would not understand the dynamics or the progression of hydrological drought on the Prairies. Small studies would certainly have been undertaken, but they would have been very local in scale, which would have severely limited the benefits. Such studies would not have provided the big picture, nor could they have furthered our understanding of and ability to adapt to drought.

Without CFCAS funding, the first attempt in Canada to systematically reconstruct and deterministically forecast drought in real time for the entire Prairie Provinces would not have occurred. The methodology developed by DRI can potentially be used for the operational management of drought impacts over large areas.

In terms of next steps, each DRI Investigator now has a strong base on which to build in terms of research papers and collaborations. Younger Investigators have gained experience in proposal writing, reporting on results, budget management and grant management. Most if not all Investigators have developed ideas that will move their research forward in the future.

Without funding from CFCAS, graduate students would not have received support and research assistants would not have been hired. Currently, DRI research "graduates" hold important positions in Manitoba Water Stewardship, Manitoba Hydro, Environment Canada, where they are using their skills in analysis and forecasting.

5. DRI IMPLEMENTATION

5.1. Delivery on plans and objectives

The project milestones and deliverables in the Network Research Agreement included:

1) Annual Research Progress Reports sent to the Network Management Office,
2) The Scientific Committee's recommendations to the Board of Directors,
3) Annual Science Meetings were held to report on progress and identify next year's research priorities and Science Committee and Board of Directors meetings to approve work plans and budgets,
4) Annual Progress reports, and
5) Final report to CFCAS.

The following milestones and deliverables articulated in the DRI Network Research Agreement have been met and this report constitutes the final report for CFCAS.

At the scale of the work plan, each funded theme had deliverables and milestones that are articulated in some extent in the theme summaries. Core integrating activities were central to realizing these milestones and the most productive Investigators were those who contributed most actively to these deliverables. In addition, since a number of specific sub-projects were conceived either as parts of graduate theses or projects for term research associates, they were scoped into "do-able" projects that fit easily within DRI's time frame and resources. Establishing the presentation of new and original work at each annual DRI workshop as a Network requirement helped to ensure that milestones were met. DRI succeeded in providing the following deliverables in a timely way:

1) Synthesis showing the development of the 1999-2005 drought.
2) Improved hydrological models have been developed (several hydrologic models are still under development and are expected to be completed by the end of 2011). These developments included the collection of data to test the model in different geographical and climatic situations.

3) A number of process study objectives were achieved and provided student training in the form of M.Sc. and Ph.D. theses and subsequent refereed publications.
4) Assessments of various methods for agricultural drought characterization based on the current drought period.
5) Datasets and an analysis framework were developed to facilitate an improved understanding of how and where droughts form, migrate and terminate. Numerous papers have been published.
6) A DRI data legacy was produced by completing the collection on metadata in the summer of 2009 and the data by the summer of 2010.
7) Studies of hydrological process (including snow, ET and groundwater) were completed using past and current research basin observational records. This was achieved by using data records from the Bad Lake and St. Denis research sites as well as remote sensing imagery and eddy correlation measurements.
8) Assessments of the role of land, groundwater and atmospheric processes in influencing precipitation were undertaken by analyzing historical data and carrying out well-designed short-term field studies.
9) These deliverables were fully completed and the results will be gathered in a special *A-O* issue to be published in 2011.
10) As a component of the DRI outreach plan a Professional Document was prepared for government managers and educational personnel which summarizes the results of DRI in layman's terms. Copies of this document are being widely circulated.

5.2. Results or outputs that have been taken up by user groups.

There are three main groups that DRI has targeted with its research. These include the climate and weather community (including MSC forecast offices), water resource managers and the agricultural sector. In many cases DRI research results have been published and are available for application by operation agencies/applications, while in other cases the DRI Researcher is working closely with the Investigator to implement the results. Examples of DRI research that have benefited each of these sectors is given below. There are a number of examples of research outputs that have been taken up by user groups.

Climate and Weather:

DRI research has provided constraints and benchmarks for climate models. For example, the relationships between precipitation anomalies and anomalies in cloud characteristics and the processes of virga that have been documented in DRI need to be reproduced by the climate models that are being used to understand drought. The use of the relationships between cloud and precipitation could also benefit operational forecasts services.

The development of a drought synthesis and climatology of Prairie water and energy budgets were compiled in part to support model validation, the development of statistical prediction schemes and climate change studies. These studies can also benefit drought monitoring programmes with new insights into the strengths and weaknesses of individual indices. Results from the Prairie drought trends studies also have potential applications for policy development. In addition, a classification scheme for drought was developed. It includes a six-stage drought evaluation system (including onset, growth, peak, decline and termination). This schema will help improve the planning and preparation involved in coping with droughts through an improved ability to identify the different stages of drought. The information would be valuable for local and national drought plans, actions and monitoring.

A number of DRI studies have provided insight into the processes and relationships that affect the seasonal prediction of drought: For example, results have shown the relationship between large-scale planetary circulation patterns and drought, including the role of Sea Surface Temperatures in forcing large-scale circulation patterns. Furthermore, the multiple drivers of drought and the interplay between synoptic-scale, mesoscale, and planetary-scale processes have been elucidated. The results could be of use for operational forecasters of both weather and climate and researchers.

Water Management:

In the West Nose Creek watershed, the research groundwater monitoring network that was mainly built from existing water supply wells has been adopted by the County of Rocky View as the basis for a larger-scale groundwater monitoring network. This is a direct contribution of DRI to water resource management on the Canadian Prairies.

The source and nature of hydrological memory during drought or non-drought conditions and its relation to wetland storage volume in a basin has been developed. Ducks Unlimited Canada and provincial water departments view this result as an important argument for wetland conservation. DRI research has shown how wetland water storage controls streamflow generation in the Prairie landscape and the implications of wetland drainage on streamflow. This result has attracted funding from all Prairie Provinces and the federal government for a demonstration project on Smith Creek, Saskatchewan.

Agriculture:

DRI research has shown that drought indices based on evaporative demand and water balance (supply versus demand) are more strongly correlated to wheat yield and quality than indices based on water supply (precipitation) or crop water use. The research found that very similar values of ET were obtained using either the modified PAMII model or the FAO56 Penman-Monteith approach. Furthermore, ten-day composite MODIS NDVI data from the late June to late July period provides a good indication of crop yields by census agriculture region and can provide this information prior to the harvest of the crops. These results have helped convince groups such as GEO that they should review evapotranspiration data to see it has application for development as an Essential Climate Variable.

Dataset development has been important for users and researchers wishing to conduct an analysis of drought after DRI has concluded through a query-able metadata database that connects to datasets generated/used by DRI.

5.3. Integration and Coordination of the work of co-investigators:

DRI benefited from the network services and by promoting integrated projects. These included centralized data services, regular reporting and annual meetings, the exchange of information between Investigators and, at the highest level, the collaborative undertaking of projects and syntheses, with each Investigator bringing his or her strengths to the research challenge. Table 5.1 lists a number of these collaborations. It is evident that some Investigators made better use of this aspect of the Network than others.

Table 5.1: Coordination of Investigator/Collaborator interactions

Investigator	Co-investigator	Integration/Coordination
Barrie Bonsal	Amir Shabbar	Joint research
Barrie Bonsal	Elaine Wheaton	Co-Investigators
John Gyakum	Susan Skone (University of Calgary)	Co-Investigators
John Hanesiak	All DRI Investigators	Collaboration on synthesis paper
Henry Leighton	Ron Stewart	Co-supervisor of grad student
Henry Leighton	Kit Szeto	Provision of model output
Charles Lin	Eric Wood, Dennis Lettenmaier	Advice on use of VIC model
John Pomeroy	Lawrence Martz, Kevin Shook	Co-Investigators
John Pomeroy	Masaki Hayashi, Al Pietroniro, Al Woodbury	Collaboration in model development
Amir Shabbar	Barrie Bonsal	Joint research
Ronald Stewart	Henry Leighton	Co-supervisor of grad student
Ronald Stewart	John Hanesiak, Kit Szeto	Joint research
Geoff Strong	John Hanesiak	Joint research (UNSTABLE)
Geoff Strong	Susan Skone (University of Calgary)	Data sharing
Geoff Strong	Gerhart Rueter, Mr. Brown	Joint research
Kit Szeto	DRI Investigators	Joint research
Kit Szeto	Burkhart Rockel	Joint research
Elaine Wheaton	DRI Investigators	Exchanges of information
Al Woodbury	Charles Lin, Ken Snelgrove	Joint research

5.4. **Participation of government (federal, provincial or local), university, industry or foreign researchers.**

Government scientists have had two general classes of interactions with DRI. Four Investigators were federal scientists or managers who were also adjuncts at universities. In fact, over the course of the project two DRI Investigators became Environment Canada managers. In addition, a number of government scientists are also DRI Collaborators. Most notable in terms of substantive contributions are Dr. Kit Szeto and Amir Shabbar, both from Downsview, Ontario. Studies on drought processes have been advanced through the collaboration of Barrie Bonsal, Amir Shabbar and Kit Szeto of Environment Canada in Toronto, Ontario. Table 5.2 provides a list of Investigators who took advantage of the pools of expertise and resources maintained by the federal and provincial governments.

Table 5.2. List of interactions between DRI Investigators and government colleagues.

Investigator	Collaborator	Collaborator's Affiliation	Type of Interaction
Barrie Bonsal	Scientists at Environment Canada and SRC	Environment Canada	Joint research
Paul Bullock	Shusen Wang	CCRS	Provision of imagery and joint publication of results
Paul Bullock	Shammi Raj	Rubber Research Institute India	Data set and manuscript preparation
John Gyakum	Marco Carrera, Ron McTaggart-Cowan	Environment Canada	Research consultation
John Hanesiak	Bob Kochtubajda, Bill Burrows	Environment Canada	Joint research
John Hanesiak	Anne Walker, Chris Derksen	Environment Canada	Provision of data
Phil Harder	Steve Williams	NCAR, Boulder	Data archival
Masaki Hayashi	Daniel Itenfisu, Ralph Wright	Alberta Agriculture	Model improvement
Masaki Hayashi	Officials	MD of Rocky View	Advice and assistance
Henry Leighton	Alex Trichtcheno, Dr. Radkevitch	CCRS	Co-Investigator
Charles Lin	Hai Lin, Peter Houtekamer, Juan Sebastien	Environment Canada	Provided data
Charles Lin	Trevor Hadwin	AAFC	Provided advice
Charles Lin	Scientists	Chinese Ministry of Water Resources, Hohai University	Joint research
John Pomeroy	Al Pietroniro, Garth van	Environment	Research collaboration

	der Kamp	Canada	on hydrologic processes
Amir Shabbar	Scientists at University of Manitoba and NHRC	University of Manitoba, Environment Canada	Joint research
Ronald Stewart	Meteorologists and scientists	Environment Canada	Research consultation, analysis and the provision of data
Geoff Strong	Craig Smith, Neil Taylor, Dave Sills	Environment Canada	Joint research
Garth van der Kamp	Provincial hydrologist	Western provinces	Data sharing
Elaine Wheaton	Dan McKenney, Ted Hogg	Canadian Forestry Service	Research consultation
Elaine Wheaton	Grace Koshida	Environment Canada	Research consultation
Al Woodbury	Bob Betcher, Laura Frost, J. Wong	Manitoba Water Stewardship	Research consultation

6.0 **Dissemination and Outreach**

6.1 Dissemination of the research results, conference contributions, seminars, workshops or videos, websites or other methods of transferring the results.

DRI Investigators actively published research results and presented their findings at scientific conferences, as the following bibliography attests. The DRI website was an important vehicle for disseminating information about the latest research results, upcoming workshops, results of past workshops and publications. Papers are not posted on the DRI website but are made available upon request from individual authors. This policy was implemented after the Canadian Water Resources Journal indicated that DRI was violating their copyright rules by posting papers on the DRI website. The presentations from DRI workshops are available in .pdf format on the DRI website.

6.2 Outreach and public information activities

A number of DRI Investigators and the Network Manager have given interviews with the media about DRI, the end of CFCAS and drought in general. Investigators and Collaborators who have given interviews include: Ron Stewart (television, press and radio); John Pomeroy (press and television); Paul Bullock (television and radio); Garth van der Kamp (press); Elaine Wheaton (press), Geoff Strong (radio); and Rick Lawford (press, radio). "Whatcha going do when the well runs dry," which was run by the Western Producer, rates as one of the DRI classics. Ken

Snelgrove was featured on two occasions in articles for Memorial University journals including articles in Memorial University publications the Luminus Magazine v32, no.2 p.12-13. [Memorial University Alumini Magazine] and the Benchmarks Magazine, Winter 2007, p.12 [Faculty of Engineering Alumini Magazine].

A school curriculum (Grades 8 and 11) on groundwater is being developed and will involve drought issues. Masaki Hayashi held field workshops for schoolteachers in July 2009 and July 2010. As part of the outreach on climate change, John Gyakum is collaborating with the community of Deline, Northwest Territories, on the issue of climate change.

The Canadian Encyclopaedia entry on drought has been updated recently by Ron Stewart and Barrie Bonsal. Ron Stewart also wrote a half-page section of a new second-year university textbook that covers drought, with examples drawn from DRI. Kit Szeto also developed DRI entries for Wikipedia.

Ron Stewart has been conducting a cross-Canada lecture tour as a result of his successful application to CFCAS for a supplementary grant. The lecture series will be completed by March 31, 2011. To date the following lectures have been given:.

2010	
September 21	Simon Fraser University
October 21	University of Alberta
November 4	University of Calgary
November 5	University of Manitoba
November 17	University of Lethbridge
November 30	University of British Columbia
2011	
January 12	University of Winnipeg
January 17	Memorial University
*March 11	Institute for Catastrophic Loss Reduction, Toronto*
*March 19	Manitoba Museum, Winnipeg*

The DRI professional Document is also part of the DRI outreach. This 120-page document, entitled *The 1999-2005 Canadian Prairies Drought: Science, Impacts and Lessons*, will be circulated widely.

These efforts have all helped to popularize climate science among the public, particularly in Western Canada.

6.3 Data and Information Services and the DRI Data Legacy:

A significant challenge for the DRI Network arose from the fact that the data and information necessary to conduct the analysis of this multi-year drought was primarily collected by agencies external to DRI before the formal research programme began. Challenges and hurdles were faced in collecting, managing, integrating and archiving various data from global to local domains. Specific issues included data sharing policies, data access, data formats, spatial discontinuities in datasets across provincial and national boundaries, and data stewardship. The experiences of this endeavour resulted in systems and data collections which facilitated the activities of the Network as well as providing a stepping stone for future drought research in Canada.

The data system envisioned by DRI Data Management Team provided a range of services for accessing the data using various platforms based on the following four principles. First, through the DRI Data and Information System, DRI provided information on its latest research results about drought to stakeholders to provide them with better information on drought monitoring, drought prediction and guidance on drought response. Second, the DRI data policy that was developed and approved by the DRI Board of Directors advocated open access for all data but also respected the right of those Investigators who collect field data to have time for quality control and analysis of these data before making them open to the broader research and applications communities. The DRI data policy also respected the restrictions that data suppliers may have placed on their data. Third, all users of DRI datasets will respect the effort that goes into collecting and processing these data and properly reference the source of the data and the DRI project. Lastly, as a Canadian project, DRI fully cooperated with GEO and viewed itself as a prototype for how GEO could interface with research projects in the future. To meet these principal requirements, a conceptualized Data and Information System was distributed over a variety of platforms including integrated central servers, Investigators' local computer systems and a website to deliver integrated services to Iinvestigators, the drought community and the public was envisioned.

The Data Access Interface (DAI) functions as the central server for the DRI Network and contains many large datasets. The data holdings on this system include model outputs from Canadian, U.S., British and French regional and global climate models, Environment Canada observational data and remote sensing data from the Canadian Centre for Remote Sensing. The number of datasets on this system continues to increase. Other than the CRCM, access to the data is limited to registered users from the partner organizations which funded DAI's development. Some datasets were assembled specifically for DRI and included groundwater observation wells for the Prairie Provinces and gridded Canadian land surface data.

The DRI web site **(www.drinetwork.ca)** provided a user-friendly entry point to the different data sources within the DRI data system and elsewhere on the internet. In addition to hosting a selection of data, the DRI website provided an extensive list of datasets, organizations and projects related to drought on the Prairies and globally. This list's objective was to provide the investigators of DRI with a one stop shop to find drought related data and information.

The large volume of data collected and generated by DRI over the past five years is a rich resource that DRI will make available to future users. In order to make these data available after

DRI, an integrated data system for consolidating regional information about drought was developed. The DRI Data Legacy System not only serves the needs of the research community but provides governments and the public with better access to information about the drought phenomenon. The DRI Data Legacy was formally integrated into the 2009-2011 GEO work plan under Task WA-06-02b and was accepted as a Type 3 Initiative in response to a GEO Call For Participation (CFP) for Earth Observations in Decision Support (GEO, 2010).

The DRI Data Legacy includes a metadatabase that is coupled with a user-friendly web interface which utilizes Google Map technology to add a spatial component to searches and results. This centralized metadata database provides links to centralized services available through DAI and distributed data on other computer systems. The goal of these services is to allow users to find relevant drought data that can be tailored to their location of choice. Optional conditions to narrow results include text search, spatial bounding, temporal extent, keywords and data source.

The metadata meets the requirements for the core components of the ISO 19115 metadata specification. This standard was selected due to its current broad acceptance at many levels, its interoperability with other standards and its emerging presence as the global standard. This attribute allows DRI metadata to be potentially interoperable with global data discovery systems. Data included in the DRI legacy were collected from the Investigators. They cover a wide array of formats, sizes and variables, which made the development of a systematic data storage system challenging given the available resources. In addition, the potential amount of available data was reduced due to the restrictive data-sharing policies of several original data providers. Efforts were made to either establish connections to these datasets through the Investigators or original data providers and to include them as part of this distributed archive.

A data legacy policy was designed to define the contents of the data legacy and how it would be designed and operated for public access. It is a non-restrictive policy for licensed use, as the majority of the data available were provided to DRI under licensed use policies. No data were made available in the legacy if its source data policy would be violated. By downloading the data, the user agrees to acknowledge and cite DRI and the original data sources in any publication.

Hosts for the data legacy rely on external partners who will make the DRI legacy available without funding from CFCAS. Two locations have agreed to make these services available, namely DAI and NCAR. DAI facilitated the legacy by providing a directory in its existing system for the data legacy. NCAR provided a similar space, though larger, that was able to handle the size of the large radar data archive (1.3 TB). The metadata database and the datasets were also connected by simple hyperlinks.

Many different formats are used for displaying geospatially referenced scientific data such as NetCDF, GriB and ASCII, even though they have little in common. DRI has advanced the use of Google Earth to present geoscientific data in an integrated manner. Google Earth was preferred due to its user-friendliness, the ease with which files can be shared, its cost (free), internet accessibility, the inclusion of spatial and temporal referencing and its GIS compatibility. Another major advantage of Google Earth is its very active online community, which has developed extensive resources relating to the access, manipulation and applications of Google Earth and KML files.

6.4 Acknowledgement of CFCAS support.

DRI has made it a policy to encourage all Investigators to use the CFCAS logo on the cover of their presentations and publications. In addition, DRI Investigators acknowledge CFCAS in their publications and posters and often refer to CFCAS' support during oral presentations. An example of the phrasing used is: "This work was part of the Drought Research Initiative funded, by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)." This commitment carries over into the future for all publications and presentations based on the support that CFCAS has provided. In addition, users of DRI Data Legacy data have been asked to acknowledge and cite DRI and its funding source, CFCAS, if and when they utilize the data.

8.0 Training

DRI has made a substantial contribution to Canadian science through the training of highly skilled personnel who can conduct research projects, teach and lead scientific activities. Over the duration of DRI, more that 21 M.Sc. students, 14 Ph.D. students, and ten early career scientists received funding support. A brief list of the majority of these students and young scientists is given in Table 8.1.

Table 8.1. List of students and research assistants who have participated in DRI.

Investigator	Student	Level	Current Placement
Barrie Bonsal	Jerry Kermack	M.Sc.	Medical Leave
Paul Bullock	Mark Gervais	M.Sc. Grad	Manitoba Hydro
Paul Bullock	Dr. Manasah Mkhabela	Post-doctoral fellow	University of Manitoba Research Associate
John Gyakum	Jessica Turner	Ph.D.	N/A
John Gyakum	Florian von Appen	M.Sc.	N/A
John Gyakum	Alain Roberge	M.Sc.	N/A
John Gyakum	Katherine Emma Knowland	M.Sc.	N/A
John Gyakum	David Small	M.Sc.	N/A
John Gyakum	Lisa Hryciw	M.Sc.	N/A
John Hanesiak	Julian Brimelow	Ph.D. Student	Finishing degree
Masaki Hayashi	Getachew A. Mohammed	PDF	PDF University
Masaki Hayashi	Ligang Xu	PDF.	Chinese Academy of Sciences
Masaki Hayashi	Erick Burns	Ph.D.	US Geological Survey
Masaki Hayashi	Lisa Grieef	M.Sc.	Alberta Environment

Masaki Hayashi	John Jackson	M.Sc.	Industry
Masaki Hayashi	Chris Farrow	M.Sc.	University
Masaki Hayashi	Sangeeta Guha	M GIS	Alberta Environment
Masaki Hayashi	Rui Chen	M.GIS	Industry
Masaki Hayashi	Nathan Green	B.Sc.	University
Masaki Hayashi	Matthew Eckfeld	B.Sc.	Industry
Henry Leighton	Two students	M.Sc.	Federal government
Charles Lin	Dr. Lei Wen	Research Associate	McGill University
Charles Lin	Rabah Aider	M.Sc.	N/A
Alain Pietroniro	Dean Shaw	PhD	N/A
Alain Pietroniro	Saul Marin	PDF	Private Sector
Alain Pietroniro	Laura Comeau	MASc	N/A
Alain Pietroniro	Habib Mazaheri	PhD	On-going
Alain Pietroniro	Muluneh Admass Mekonnen	PDF	On-going
John Pomeroy	Dr. Kevin Shook	Research Associate	University of Saskatchewan Centre for Hydrology
John Pomeroy	Robert Armstrong	Ph.D. student	AAFC
John Pomeroy	Xing Fang	M.Sc.	University of Saskatchewan Centre for Hydrology
Ken Snelgrove	Sitotaw Yirdaw	Ph.D.	Manitoba Water Stewardship?
Ken Snelgrove	Clement Agboma	Ph.D.	Continuing Ph.D. studies
Ron Stewart	Erin Evans	M.Sc.	Calgary Air Quality specialist
Ron Stewart / Henry Leighton	Heather Greene	M.Sc.	Meteorologist -Environment Canada, Edmonton
Ron Stewart / Henry Leighton	Trudy McCormick	M.Sc.	Forecaster training course, Environment Canada
Ken Snelgrove	Clement Agboma	PhD	Consultant
Ken Snelgrove	Sitotwa Yirdaw	PhD	Consultant
Ken Snelgorve	Matt Carter	B. Eng	M. Eng.
Ken Snelgrove	Seth Bennett	B. Eng	M. Eng
Ron Stewart	William Henson	PDF	Research Associate at McGill University
Ron Stewart	Hannah Carmichael	Research Associate	B.Ed. student at St. Mary's University

Geoff Strong	Brown	M.Sc.	
Kit Szeto	5 Co-op students	B.Sc.	
Kit Szeto	Student	Ph.D.	Government of Pakistan
Garth van der Kamp	Student	M.Sc.	
Garth van der Kamp	Research Assistant	PDF	
Elaine Wheaton	Research Assistants	On-job training	
Al Woodbury	Dr. Lei Wen	PDF	
Al Woodbury	Dr. Youssef Loukili	PDF	
Al Woodbury	Smrita Joshi	Ph.D.	
Al Woodbury	Alireza Hezazi	Ph.D. student	
Al Woodbury	Kibreab Assefa	Ph.D. student	

8.0 General Comments for CFCAS

By far, the strongest recommendation to come from respondents was a call for CFCAS to be maintained. This marks a recognition of the importance of the DRI Network and a well-founded perception that CFCAS is critical for the advancement of climate, weather and water science in Canada. It has also contributed to the maintenance of a healthy climate community in Canada, particularly in the academic environment, and benefits the Canadian public in terms of independent and authoritative advice on the country's future development. It is clear that CFCAS is making every effort to secure a renewal of its funding and its mandate. This recommendation is a request to continue and, where possible, to strengthen its efforts.

Individual Investigators expressed views about how CFCAS could have supported the areas they felt were important. Perhaps the fact that these points were relatively isolated reflects the focus and success CFCAS has had on supporting the broad areas where networks need support. It was suggested that CFCAS could play a larger role in the data management aspects of the research it funds. For example, it could play a role in defining best practices and policies surrounding data management. This type of proactive encouragement could facilitate the collection and archiving of research data.

In general, DRI Investigators strongly believe that the government should support the continuation of CFCAS. There is a recognized need for this type of research because it fills a knowledge gap regarding the fundamental processes that determine the variability of Canada's climate, weather and water resources. In conclusion, it should be noted that the support and guidance provided by the CFCAS programme office has been very timely and helpful throughout the project. Its contributions to the success of DRI are gratefully acknowledged.

Appendix 1
Acronym List

AAFC	Agriculture and Agri-Food Canada
ADA	Assiniboine Delta Area/Aquifer
AGU	American Geophysical Union
AMO	Atlantic Multi-decadal Oscillation
A-O	*Atmosphere-Ocean*
BERMS	Boreal Ecosystem Research and Monitoring Sites
CANGRID	Canadian Grid
CCRS	Canada Centre for Remote Sensing
CCSN	Climate Change Scenarios Network
CFCAS	Canadian Foundation for Climate and Atmospheric Sciences
CFS	Canadian Forestry Service
CGU	Canadian Geophysical Union
CLASS	Canadian Land Surface Scheme
CLIVAR	Climate Variability and Predictability
CMOS	Canadian Meteorological and Oceanographic Society
CRCM	Canadian Regional Climate Model
CRHM	Cold Region Hydrological Model
CRU	Climate Research Unit
DAI	Data Access Interface
DEWS	Drought Early Warning System exercise
DRI	Drought Research Initiative
DUC	Ducks Unlimited Canada
ECMWF	European Centre for Medium and Long-Range Forecasting
ENSO	El Niño/Southern Oscillation events
ERA40	European Centre for Medium and Long-Range Forecasting (ECMWF) Reanalysis
ET	Evapotranspiration
gCLASS	Groundwater CLASS
GEC3	Global Environmental and Climate Change Centre
GEM	Canadian Graphical Environmental Manager
GEO	Group on Earth Observations
GEOSS	Global Earth System of Systems
GIS	Geographic Information System
GOWN	Alberta Environment Groundwater Observation Well Network
GRACE	Gravity Recovery and Climate Experiment
HAL	Hydrometeorology and Arctic Laboratory
HFP	Historical Forecasts Project

IP3	Improved Processes and Parameterisation for Prediction in Cold Regions
ISCCP	International Satellite Cloud Climatology Project
IUGG	International Union of Geodesy and Geophysics
MD	Municipal District
MEC	Modélisation Environnementale et Communautaire
MESH	MEC Surface and Hydrology Model
MODIS	Moderate Resolution Imaging Spectroradiometer
MWS	Manitoba Water Stewardship
NAO	North Atlantic Oscillation
NARR	North American Regional Reanalysis
NCEP	National Centers for Environmental Prediction
NDAM	North American Drought Monitor
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
NPI	Normal Precipitation Index
NRCan	Natural Resources Canada
NSERC	Natural Sciences and Engineering Research Council
PAC	Partners Advisory Committee
PAM	Prairie Agrometeorology Model
PAMII	Canadian Prairie Agrometeorological model
PAW	Plant Available Water
PDO	Pacific Decadal Oscillation
PDSI	Palmer Drought Severity Index
PFRA	Prairie Farm Rehabilitation Administration
PNA	Pacific North American
PPRB	Prairie Provinces Water Board
REDE	Research for Disaster-reduction from Extremes
RPN	Recherche Prévision Numérique (RPN)
RZSM	Root-zone soil moisture
SCD	Snow cover duration
SMAPI	Soil Moisture Anomaly Percentage Index
SOI	Southern Oscillation Index
SPI	Standard Precipitation Index
SRB	Surface Radiation Budget
SSM/I	Special Sensor Microwave Imager
SST	Sea Surface Temperature
SWE	Snow water equivalent
TOA	Top-of-atmosphere

US GEO	U.S. Group on Earth Observations
VIC	Variable Infiltration Capacity
VSMB	Versatile Soil Moisture Budget
WCRP	World Climate Research Programme
WC2N	Western Canadian Cryospheric Network

Appendix B

DRI Prairie Hydrology Workshop
Hilton Garden Inn, Saskatoon, Saskatchewan, November 18, 2009

About 80 people from the three Prairie Provinces, British Columbia and Ontario attended this one-day workshop in Saskatoon. The workshop was organized by the Centre for Hydrology of the University of Saskatchewan as part of its contribution to the Drought Research Initiative in order to promote scientific exchange on aspects of Prairie hydrology with various science organizations with an interest in the Prairie region.

The workshop talks were organized around themes of Drought and Climate Change, Distinctive Aspects of Prairie Hydrology and Prairie Water Availability, with a total of 17 presentations. Presenters consisted of scientists, managers, academics and graduate students from Environment Canada, the University of Manitoba, the University of Saskatchewan, the University of Regina, Guelph University, the University of Alberta, Agriculture and Agri-Food Canada and the Saskatchewan Watershed Authority. The agenda, with presenters and titles is listed at the end of this report.

Three discussion sessions focused on each of the themes. The first discussion on Drought and Climate Change centred on three questions:

i) What are the major uncertainties in your understanding that need to be addressed?
ii) What are the problems in observation systems that would improve your results?
iii) What are the next steps in predicting drought and climate change hydrology in the Prairies?

Areas of uncertainty included meteorological input data, streamflow calibration data, understanding of pothole pond runoff generation and evapotranspiration. Problems in observing systems included lack of soil moisture and radiation observations, insufficient snowfall, snowpack and rainfall observations, sparse hydrometric network and uneven availability of collected data. Next steps in prediction included linking small-scale to large-scale hydrology in models in order to estimate contributing area, better incorporation of uncertainty in modelling, better data assimilation in models and including landscape change in long-term modelling.

The second discussion on Distinctive Aspects of Prairie Hydrology centred on three questions:

i) What are the known deficiencies in your research that are not related to data?
ii) How are you dealing with these problems?
iii) What is holding you back from successfully dealing with these deficiencies?

Known deficiencies in research include difficulty in parameterizing fill/spill (including initial states), dealing with the spatial variability of parameters, the necessity of improvements in modelling and unknown spatial applicability of precipitation correction equations. Deficiencies were addressed by making assumptions, investigating scales of importance, and by calibration where necessary. Factors holding back progress included personal conflicts, scaling issues (particularly for modelling of medium/large basins) and the difficulty of understanding complex phenomena such as the fill/spill of a network with a large number of wetlands covering a basin.

The third discussion on Prairie Water Availability centred on issues of water use and availability from both basin-scale studies across the Prairies and Saskatchewan-based studies led by the Saskatchewan Watershed Authority (SWA). Use of Saskatchewan waters is complex to document and distinctions must be made between allocation, use and actual water removal from the surface hydrological system. The SWA study includes a Water Use Assessment Project with a pilot project on the Swift Current Creek basin. The Groundwater Availability Project will focus on regional aquifer mapping and recharge estimation. The Surface Water Availability Project will focus initially on the Souris River basin in respect to hydroclimatic trend analysis, natural flow trend analysis and water supply availability for major basins.

Appendix C:

Bibliography:

Refereed Journal Articles:

a) Journal papers (refereed)

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van der Kamp G. and A. G. Barr, 2010. The CCP-Fluxnet Canada network and the interplay between energy, water and carbon uptake in the landscape. Invited presentation, Session on carbon cycling of Canadian forests and peatlands, CGU-CMOS conference, May 30-June 4, 2010, Ottawa.

van der Kamp, G. and M. Hayashi, 2010. Groundwater and drought in the prairies – what observation well data can tell us. Session on Drought and society, CGU-CMOS conference, May 30-June 4, 2010, Ottawa.

van der Kamp, G., 2010. The Groundwater connection. Invited presentation, CFCAS-EC Symposium on Water Security, Ottawa, May 27-28, 2010.

van der Kamp, G. 2010. Hydrology, Climate and the Threat to Wetlands. Invited Keynote Presentation. International workshop on Wetlands Management, Economics and Policy, Victoria, BC, January 13-15, 2010.

van der Kamp, G., 2009. Long-term water-level changes of prairie lakes – century scale variations of water availability. Invited presentation. DRI Prairie Hydrology workshop, Saskatoon, Nov 18, 2009

van der Kamp G. 2009. Ecohydro(geo)logy of the southern boreal forest in Saskatchewan: From piezometers to eddy-flux towers and everything between. Invited seminar, Dept of Earth and Environmental Sciences, U of Waterloo, Sept 18, 2009.

van der Kamp, G., 2009. Long-term water level changes in closed-basin lakes of the Canadian prairies and the role of groundwater. Invited keynote presentation at the Annual Conference of Alberta Environment Provincial Water Act held in Banff, AB, March 22-24, 2009.

van der Kamp, G., M. Hayashi, 2009. Prairie Wetlands and their Catchments: Hydrological Understanding and Management Implications for Drainage and Groundwater Recharge. Invited keynote presentation at the Annual Conference of Alberta Environment Provincial Water Act held in Banff, AB, March 22-24, 2009.Wang, S., Y. Yang, A. Trishchenko, Y. Luo, X. Geng, P. Bullock, and N. Mi, 2009: Drought impact characterization using remote sensing and ecosystem modeling. *2009 Joint Assembly, American Geophysical Union*, Toronto, Ontario.

Venema,H., R. Lawford, M. McCandless, D. Roy, K.Zubrycki, D. Medeiros, 2010: Lake Winnipeg Basin – confronting cultural eutrophication with new narratives for socio-ecological transformation , GCI Conference, Bonn, Germany, December 7, 2010

Wen, L., C.A. Lin, Z. Wu, G. Lu, J. Pomeroy, and Y. Zhu, 2010: Analysis of real-time Prairie drought monitoring and forecasting system. CMOS-CGU Congress, Toronto, .

*Wheaton, E., S. Kulshreshtha, V. Wittrock, and G. Koshida, 2008: Dry Times: Lessons from the Canadian Drought of 2001 and 2002. *Can. Geog.*, **52**, 241-262.

Wu, Z., G. Lu, L. Wen, and C.A. Lin, 2010: A real-time drought monitoring and forecasting system in China. 5th International Symposium on Integrated Water Resources Management and 3rd International Symposium on Methodology in Hydrology, Nanjing, China; in press.

Yirdaw, S.Z., K.R. Snelgrove, F.R. Seglenieks, C.O. Agboma, and E.D. Soulis, 2009: Assessment of the WATCLASS hydrological model result of the MacKenzie River Basin using the result of the GRACE satellite total water storage measurement. *Hydrol. Processes*, **23**, 3391-3400.

Presentations in major national and international conferences:

Agboma, C. O. and K.R. Snelgrove, 2006: Non-Parametric Approach for Trend Delineation in the Canadian Prairie. Eos Transactions. AGU, 87(52), Fall Meeting Supplement, Abstract GC41A-1034.

Armstrong, R., J.W. Pomeroy, and L. Martz, 2007: Problems in estimating evaporation in Prairie environments. *DRI Evaporation Workshop*, Saskatoon, Saskatchewan.

Armstrong, R., J.W. Pomeroy, and L. Martz, 2008: Examining the spatial variability of actual evaporation under clear skies. *Canadian Geophysical Union Meeting*, Banff, Alberta.

Armstrong, R., J.W. Pomeroy, and L. Martz, 2009: Progress towards calculating actual evaporation over the Canadian Prairie region during drought. *DRI Drought Characterization Workshop*, Winnipeg, Manitoba, 2009.

Armstrong, R., J.W. Pomeroy, and L. Martz, 2009: Spatial variability of actual evapotranspiration across the Canadian Prairies during drought. *Canadian Geophysical Union Meeting*, Toronto, 2009.

Armstrong, R., J.W. Pomeroy, and L. Martz, 2009: Variations in growing season actual evapotranspiration across climatological gradients in the Prairie region of Western Canada. *AGU Ecohydrology Chapman Conference*, Sun Valley, Idaho, October 2009.

Armstrong, R., J.W. Pomeroy, and L. Martz, 2010: Surface hydrological components of Prairie drought. *DRI Saskatchewan Users Workshop*, Regina, Saskatchewan, 2010.

Bonsal B.R., 2006: Droughts in Canada: An Overview. *Annual American Geophysical Union Meeting*, December 11-15, 2006, San Francisco, California.

Bonsal B.R., 2007: Droughts in Canada: An overview. *Annual CMOS/CGU Meeting*, May 28 – Jun 1, 2007, St. John's, Newfoundland.

Bonsal, B.R., 2008: The drivers of hydro-climate variability in Western Canada. *Past and Future Hydroclimatic Variability: Applications to Water Resource Management in the Prairie Provinces*, March 17-18, 2008, Canmore, Alberta.

Bonsal, B.R., and A. Shabbar, 2008: Large-scale SST patterns and teleconnections associated with the 1999 to 2005 Canadian Prairie drought. *Drought Research Initiative Annual Workshop*, January 17-19, 2008, Calgary, Alberta.

Bonsal, B.R., 2009: Droughts in Canada. *Research for Disaster-reduction from Extremes (REDE) Workshop*, May 20-21, 2009, Winnipeg, Manitoba.

Bonsal, B.R., and C. Cuell, 2009: An assessment of the 500mb synoptic types associated with the 1999-2004 Canadian Prairie drought. *Drought Research Initiative Annual Workshop*, January 26-28, 2009, Regina, Saskatchewan.

Bonsal, B.R., and C. Cuell, 2009: An assessment of mid-tropospheric circulation patterns associated with Canadian Prairie droughts. *CMOS Annual Workshop*, June 1-4, 2009, Halifax, Nova Scotia.

Bonsal, B.R. 2010: Droughts in Canada: A review. *AMS Annual Meeting*, January 20-21, 2010, Atlanta, Georgia.

Bonsal, B.R., A. Shabbar, and K. Szeto, 2010: Atmospheric and oceanic variability associated with growing season droughts and pluvials on the Canadian Prairies. *CMOS Annual Workshop,* June 1-4, 2010, Ottawa, Ontario.

Burns, E.R., L.R. Bentley, M. Hayashi, S.E. Grasby, and D.G. Smith, 2006: A new paradigm for the Paskapoo aquifer system: Evidence, implications, and modeling. *Joint annual meeting of the Canadian Geophysical Union and the Canadian Society of Soil Science*, Banff, Alberta, May 14-17, 2006.

Comeau, E. L., ,A. Pietroniro and M.N. Demuth, 2009: Glacier contribution to the North and South Saskatchewan Rivers., *Hydrol. Process,* 23.

*Diaz, P., S. Kulshreshtha, B. Matlock, E. Wheaton, and V. Wittrock, 2008: Rural Community and Vulnerability to Climate Change: Case Studies of Cabri and Stewart Valley in

Southwestern Saskatchewan. *Klima 2008/Climate 2008 Web Conference*, http://www.climate2008.net/index.html?a1=pap&cat=4&e=38

Fang, X., 2006: Spatially distributed modelling of snow redistribution, melt, infiltration and runoff. *St. Denis NWA Wetland Workshop, National Hydrology Research Centre*, Saskatoon, Saskatchewan, January 31, 2006.

Fang, X., 2007: Snow accumulation, snowmelt and snowmelt runoff to Prairie ponds. *St. Denis NWA Science and Planning Workshop*, *National Hydrology Research Centre*, Saskatoon, Saskatchewan, April 3, 2007.

Fang, X., and J.W. Pomeroy, 2007: Effects of drought on Canadian Prairie wetland snowmelt hydrology. *CMOS-CGU-AMS Congress 2007: Air Ocean, Earth and Ice on the Rock, Canadian Geophysical Union 33rd Annual Meeting*, St. John's, Newfoundland, May 28 – June 1, 2007.

Fang, X., and J.W. Pomeroy, 2007: Model scale comparison for wind redistribution of snow in the Canadian Prairies. *Canadian Geophysical Union – Hydrology Section 6th Annual Student Meeting Prairie Regions*, Calgary, Alberta, January 27, 2007.

Fang, X., and J.W. Pomeroy, 2009: Drought impacts on Prairie snow hydrology. *Drought Research Initiative Hydrology Workshop*, Saskatoon, Saskatchewan, November 18, 2009.

Fang, X., J.W. Pomeroy, T. Brown, C. Westbrook, X. Guo, and A. Minke, 2009: Using field surveys and LiDAR to derive parameters for uncalibrated spring streamflow prediction using the cold regions hydrological model. *IP3 & WC2N Networks Joint Annual Workshop*, Lake Louise, Alberta, October 14-17, 2009.

Hayashi, M., and G. van der Kamp, 2007: Using prairie pothole analogues to understand the hydrological response of closed lake systems. *Annual Meeting of the Geological Society of America*, Denver, Colorado, October 28-31, 2007.

Hayashi, M., and G. van der Kamp, 2008: Effects of depth-permeability distribution on groundwater exchange and water balance of prairie wetlands. *Ninth Joint Groundwater Specialty Conference of the International Association of Hydrogeologists - Canadian National Chapter and the Canadian Geotechnical Society*, Edmonton, September 21-24, 2008.

Hayashi, M., and G. van der Kamp, 2008: Groundwater-wetland ecosystem interaction in the semiarid glaciated plains of North America. *Annual Meeting of the Canadian Geophysical Union*, Banff, Alberta, May 11-14, 2008.

Hayashi, M., and G. van der Kamp, 2008: Interaction of groundwater with prairie wetland ecosystems in Canada. *36th Congress of the International Association of Hydrogeologists*, Toyama, Japan, October 26-31, 2008.

Hayashi, M. and L. Xu, 2009: Watershed-scale modelling of depression-focussed groundwater recharge in the Canadian Prairies. *Joint Assembly of American Geophysical Union, Canadian Geophysical Union, Geological Association of Canada, Mineralogical Association of Canada, and International Association of Hydrogeologists-Canadian National Chapter*, Toronto, May 24-27, 2009.

Jackson, J., R. Chen, and M. Hayashi, 2007: Testing the Versatile Soil Moisture Budget model for groundwater recharge estimation in a northwest Canadian Prairie setting. *Joint Annual Meeting of the Canadian Meteorological and Oceanographic Society, Canadian Geophysical Union, and American Meteorological Society*, St. John's, Newfoundland, May 28 - June 1, 2007.

Koshida, G., E. Wheaton, and V. Wittrock, 2008: The 2001-2002 Canadian Drought Experience: Lessons Learned. *North American Drought Monitor-Canadian Workshop*, October 15, 2008, Ottawa, Ontario, 27 pp.

Koshida, G., E. Wheaton, V. Wittrock, E. Stratton, and S. Butt, 2008: Before the tap runs dry: Identifying user needs and designing better drought products. *North American Drought Monitor-Canadian Workshop*, March 5-6, 2008 Guelph, Ontario, 38 pp.

Loukili, Y., A.D. Woodbury, and K.R. Snelgrove, 2006: SABAE-HW – an enhancement of the water balance prediction in the Canadian Land Surface Scheme. *2006 San Francisco, AGU Fall Meeting*, December 11-15, 2006.

Marin, S.,G.van der Kamp , A. Pietroniro, B. Davison and B.Toth, 2011: Use of Observation Well Records for Confined Aquifers to Evaluate Modelling of Areal Evapotranspiration,. *Journal of Hydrology.(Accepted)*

Meinert, A., B.R. Bonsal, and E. Wheaton, 2009: Capturing the dynamics of the 1999-2005 Canadian Prairie drought using the SPI and PDSI**.** *DRI Precipitation and Drought Indices Workshop*, April 30, 2009, Toronto, Ontario.

Pomeroy, J.W., R. Granger, N. Hedstrom, T. Brown, A. Pietroniro, L. Martz, R. Armstrong, and X. Fang, 2006: Land surface hydrological processes and modelling. *Drought Research Initiative 1st Annual Workshop*, Saskatoon, Saskatchewan, January 11, 2006.

Pomeroy, J.W., R. Armstrong, X. Fang, T. Brown, L. Martz, A. Pietroniro, and R. Granger, 2007: Land surface hydrological processes and modelling. *Drought Research Initiative 2nd Annual Workshop*, Winnipeg, Manitoba, January 12, 2007.

Pomeroy, J.W., and X. Fang, 2007: Recent advances in modelling the sublimation of blowing snow on the Canadian Prairies. *Drought Research Initiative Evaporation Workshop*, University of Saskatchewan, May 17, 2007.

Pomeroy, J.W., X. Fang, R. Armstrong, and K. Shook, 2007: Prairie drought hydrology prediction using the Cold Regions Hydrological Model. *Drought Research Initiative Prediction Workshop*, McGill University, Montreal, Quebec, September 20, 2007.

Pomeroy, J.W., X. Fang, A. Minke, C. Westbrook, and X. Guo, 2008: Prairie wetland hydrology processes and modelling. *Prairie Habitat Joint Venture (PHJV) Science & Policy Forum 2008*, Saskatoon, Saskatchewan, April 8-9, 2008.

Pomeroy, J.W., K. Shook, R. Armstrong, and X. Fang, 2008: Hydrology of Prairie droughts. *Drought Research Initiative 4th Annual Workshop*, Regina, Saskatchewan, January 27, 2008.

Pomeroy, J.W., K. Shook, R. Armstrong, X. Fang, T. Brown, and L. Martz, 2008: Canadian hydrological drought: Processes and modelling. *Drought Research Initiative 3rd Annual Workshop*, Calgary, Alberta, January 17, 2008.

Pomeroy, J.W., X. Fang, C. Westbrook, A. Minke, X. Guo, K. Shook, and T. Brown, 2009: Impact of Prairie wetland drainage and land use change on spring streamflow. *Drought Research Initiative Hydrology Workshop*, Saskatoon, Saskatchewan, November 18, 2009.

Pomeroy, J.W., 2010: Water prescriptions for a dry land – How the West can prepare for drought. *Partnership Group on Sciences and Engineering "Bacon and Eggheads"*, invited talk to MPs and Senators, Parliament of Canada, Ottawa, May 2010.

Pomeroy, J.W., 2010: Canadian Prairie Drought. *ISAC3 workshop*, Lanzhou, China. September 2010.

Pomeroy, J.W., K.R. Shook, R.N. Armstrong, and X. Fang, 2010: Drought, climate variability and water resources in Western Canada. *The 3rd International Symposium on Arid Climate Change and Sustainable Development (ISACS)*, Lanzhou, China, September 8-10, 2010.

Shaw, D., L.W. Martz and A.Pietroniro, 2011: Topographic Analysis for the Prairie Pothole Region, *Hydrological Processes,* (Accepted with revision)

Shook, K.R., and J.W. Pomeroy, 2008: Stationarity analyses of historical Canadian Prairie weather data. Why do statistical tests give differing answers?, *CGU*, May 2008.

Shook, K.R., and J.W. Pomeroy, 2009: Trends in the multiscaling of precipitation on the Canadian prairies. *Joint International Convention of the International Association of Hydrological Sciences and International Association of Hydrogeologists (IAH)*, Hyderabad, India, October 2009.

Shook, K.R., and J.W. Pomeroy, 2007: Prairie drought hydrology prediction using the Cold Regions Hydrological Model. *DRI Prediction Workshop*, Montreal, Quebec, September 20, 2007.

Shook, K.R., and J.W. Pomeroy, 2007: Prairie flood and drought mitigation. *National Workshop on Watershed Conservation*, Winnipeg, Manitoba, November 9, 2007.

Shook, K.R., and J.W. Pomeroy, 2008: Evaluating gridded datasets for physically based hydrologic modelling of drought. *Second DRI Workshop on Prediction*, Montreal, Quebec, September 28, 2008.

Shook, K.R., and J.W. Pomeroy, 2008: Testing the stationarity of historical meteorological data on the Canadian Prairies. *DRI Workshop #3*, Calgary, Alberta, January 17-19 2008.

Shook, K.R., and J.W. Pomeroy, 2009: Determining Prairie hydrological drought. *4th Annual DRI Workshop*, Regina, Saskatchewan, January 2009.

Shook, K.R., and J.W. Pomeroy, 2009: Drought impacts on Prairie land surface hydrological dynamics. *Prairie Hydrological Workshop*, Saskatoon, Saskatchewan, November 18, 2009.

Shook, K.R., and J.W. Pomeroy, 2010: Determining prairie hydrological drought by modeling. *CGU*, Ottawa, Ontario, May 2010.

Shook, K.R., and J.W. Pomeroy, 2010: Modelling drought in prairie watersheds. *2010 DRI Annual Workshop*, Winnipeg, Manitoba, May 12-14, 2010.

Shook, K.R., and J.W. Pomeroy, 2010: Modelling surface water responses to drought. *Alberta DRI User's Workshop*, Edmonton, Alberta, April 6, 2010.

Siemens, E., B.R. Bonsal, E. Wheaton, and N. Nicolichuk, 2009: Drought characterizations. *Climate Hazards Workshop*, November 25, 2009, Saskatoon, Saskatchewan.

Snelgrove, K.; and Yirdaw-Zeleke, S. (2005) GRACE satellite observations of terrestrial moisture changes and drought measurement in Western Canada. 39th Annual Congress: Sea to Sky. Canadian Meteorological and Oceanographic Society. May 31-June 3, 2005. Vancouver, British Columbia.

Snelgrove, K. R., S. Yirdaw-Zeleke, E.D. Soulis, F.R. Seglenieks (2005) *GRACE (Gravity Recovery and Climate Experiment) Measurements for Drought Monitoring?*, Observational and Modeling Requirements for Predicting Drought on Seasonal to Decadal Time Scales, Adelphi, MD, May 17-19, 2005

Stewart, R.E., 2008: Extremes around the world and their impacts. *Extremes and Ecosystems Symposium, AGU*, San Francisco, California.

Stewart, R.E., 2009: Drought and heavy precipitation: Unique and common features. *Research for Disaster Reduction for Extremes Workshop*, Winnipeg, Manitoba.

Stewart, R.E., 2010: The structure of drought. *WCRP Extremes Workshop*, Paris.

Stewart, R.E., 2010: RHP perspectives and CEOP Extremes. *GEWEX SSG*, New Delhi.

Stewart, R.E., 2010: Drought, climate change and the Canadian Prairies. *European Geosciences Union Conf*., Merida, Mexico.

van der Kamp, G., and M. Hayashi, 2006: A watershed-scale approach to groundwater-surface water fluxes in prairie wetlands. *Annual Meeting of the Geological Society of America. Philadelphia*, October 22-25, 2006.

Wheaton, E., 2008: Agriculture in a Changing Climate. *Saskatchewan Research Council Agriculture, Biotechnology and Food Division*, Saskatoon, Saskatchewan, 47 pp.

Wheaton, E., 2008: Climate Change and Agriculture: Risks and Opportunities. *2008 Saskatchewan Institute of Agrologists' Conference*, Saskatoon, Saskatchewan, April 4, 2008, 47 pp.

Wheaton, E., 2008: Risks and Rewards: Global Warming and Prairie Agriculture. *2008 Saskatchewan Assessment Appraisers' Association's Annual Professional Development Workshop*, June 18-20, 2008, Saskatoon, Saskatchewan, 50 pp.

Wheaton, E., 2008: Weathering the warming: Prairies and the world. *Saskatchewan Research Council's Business Development Lunch and Learn*, Saskatoon, Saskatchewan, 40 pp.

Wheaton, E., C. Beaulieu, J. Thorpe, and V. Wittrock, 2008: Agriculture in a warming climate. University of Saskatchewan, 78 pp.

Wittrock, V., P. Diaz, S. Kulshreshtha, B. Matlock, and E. Wheaton, 2008: Rural Community Vulnerability to Climate Change: Saskatchewan Case Studies. *Adaptation to Climate Change in the Canadian Plains, Saskatchewan Institute of Public Policy and Institutional Adaptation to Climate Change Project*, Regina, Saskatchewan, April 22, 2008, 19 pp.

Wittrock, V., S. Kulshreshtha, L., Magzul, and E. Wheaton, 2008: Droughts and Floods of the late 20^{th} and early 21^{st} Centuries on the Kainai Blood Indian Reserve. *Blood Tribe Chief and Council*, Standoff, Kainai Blood Indian Reserve, Alberta, October 21, 2008, 34 pp.

Wittrock, V., S. Kulshreshtha, L. Magzul, and E. Wheaton, 2008: Floods and Droughts / Friends or Foe? *Saipoyi Elementary School*, Standoff, Kainai Blood Indian Reserve, Alberta, October 22, 2008, 20 pp.

Wittrock, V., S. Kulshreshtha, and E. Wheaton, 2008: Vulnerability of Prairie Communities to Drought: Comparing Outlook, Taber, Hanna, and Kainai Nation. *Annual Meeting of the Institutional Adaptation to Climate Change Project*, Regina, Saskatchewan, 15 pp.

Wittrock, V., and E. Wheaton, 2008: Large and small communities and climate change. University of Saskatchewan, 109 pp.

Wittrock, V., E. Wheaton, and S. Kulshreshtha, 2008: Six Prairie Communities' Susceptibility to Drought. *61st Annual National Conference of the Canadian Water Resources Association*, June 17-19, 2008, Gimli, Manitoba, 31 pp.

Woodbury, A.D.., K.R. Snelgrove, Y. Loukili, and S. Yirdaw-Zeleke, 2005: Climate change assessment over the Assiniboine Delta Aquifer. *Geological Society America, 2005 Salt Lake City Annual Meeting*, October 16–19, 2005.

Wozniak P.R.J., M. Hayashi, L.R. Bentley, S.E. Grasby, and M. Eckfeldt, 2008: Characterization of the Paskapoo for sustainable groundwater development: A modeling approach. *Ninth Joint Groundwater Specialty Conference of the International Association of Hydrogeologists - Canadian National Chapter and the Canadian Geotechnical Society*, Edmonton, September 21-24, 2008.

Xu, L., M. Hayashi, J. Jackson, and L.R. Bentley, 2008: Estimating groundwater recharge under upland and depression using a simple soil water balance model. *Annual Meeting of the Canadian Geophysical Union*, Banff, Alberta, May 11-14, 2008.

Yirdaw S.Z. and K.R. Snelgrove, 2007: *Groundwater Storage from GRACE Over the Assiniboine Delta Aquifer (ADA) of Manitoba: Early Result*, Canadian Meteorological and Oceanographic Society and Canadian Geophysical Union Joint Meeting. May 28-June 1, 2007. St. John's, NL.

Yirdaw, S.Z.; and Snelgrove, K.R.,2006: *Validation of regional precipitation minus evaporation using a coupled GRACE driven moisture storage and measured basin runoff*. Eos Transactions. AGU, 87(52), Fall Meeting Supplement, Abstract GC41A-1031.

Journal Articles Accepted but Pending Changes:

Agboma C.O., Snelgrove, K.R., Yirdaw, S.Z. and G. van der Kamp (2009) Moisture Storage Patterns Derived from a Hydrologic Model Validated with Outputs from GRACE and Geological Weighing Lysimeters. Journal of Hydrology.

Journal Articles in Review:

Yirdaw, S.Z., and K.R. Snelgrove, Groundwater Storage from GRACE Over the Assiniboine Delta Aquifer (ADA) of Manitoba. Submitted to DRI Special Issue.

Shaw, D., L.W. Martz and A.Pietroniro,2011: The influence of surface water connectivity on runoff in a prairie pothole region, *Journal of Hydrology,* (Under review)

At each DRI Annual Workshop investigators and collaborators are expected to give presentations on their latest scientific result. These presentations are available on the DRI web site (drinetwork.ca) and have not been listed here.

Posters:

Armstrong, R., J.W. Pomeroy, and L. Martz, 2007: Evaluation of evaporation estimation methods during a summer drying period. *Canadian Geophysical Union Meeting*, St. John's, Newfoundland, 2007.

Fang, X., and J.W. Pomeroy, 2006: Prairie snowmelt runoff sensitivity analysis to drought. *Joint Meeting of the Canadian Geophysical Union and the Canadian Society of Soil Science, Canadian Geophysical Union 32nd Annual Meeting*, Banff, Alberta, May 14-17, 2006.

Fang, X., and J.W. Pomeroy, 2007: Prairie snowmelt runoff sensitivity analysis to drought. *Drought Research Initiative Annual Workshop 2*, Winnipeg, Manitoba, January 12, 2007.

Fang, X., and J.W. Pomeroy, 2008: Spatial scale for modelling blowing snow. *Drought Research Initiative Annual Workshop 3*, Calgary, Alberta, January 17, 2008.

Fang, X., J.W. Pomeroy, T. Brown, X. Guo, and C. Westbrook, 2009: Hydrological modelling of a Canadian Prairie wetland basin. *American Geophysical Union and Canadian Geophysical Union Joint Assembly*, Toronto, Canada, May 24-27, 2009.

Gervais, M., P.R. Bullock, and R. Raddatz, 2008: Modeled evapotranspiration for spring wheat from the 2nd generation prairie agrometeorological model. *Canadian Society of Soil Science Annual Meeting*, Prince George, British Columbia, July 2008

Gervais, M., and P.R. Bullock, 2008: Calibration of the 2nd generation Prairie agrometeorological model for spring wheat. *3rd Annual Drought Research Initiative Workshop*, January 17-18, Calgary, Alberta.

Mkhabela, M., P.R. Bullock, and M.D. Gervais, 2009: Environmental indicators of agricultural drought impacts on spring wheat in Western Canada. *4th Annual Drought Research Initiative Workshop*, Regina, Saskatchewan, January 2009.

Pomeroy, J.W., and X. Fang, 2007: Spatial scale for modelling blowing snow. *American Geophysical Union 2007 Fall Meeting*, San Francisco, California, December 10-14, 2007.