PUBLIC VERSION OF

THE 2009 ANNUAL PROGRESS REPORT FOR THE DROUGHT RESEARCH INITIATIVE (DRI)

(This report reflects the status of DRI research and legacy development as of December 31, 2009)

Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)
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Project Title: Drought Research Initiative

1. Introduction

The Drought Research Initiative (DRI) was established to address scientific and societal issues associated with the multiyear drought of 1999 – 2004/2005 in western Canada. The overall objective of DRI is "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". The strategy of focusing on particular time periods or events is a common one, although not often used for drought research.

To address its overall objective, the DRI network has focused on five research themes:

- 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.

The DRI research network has been largely funded by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS). As outlined in this report, it also relies on in-kind contributions from a number of federal and provincial government departments and leverages the research support provided by research councils and other funding agencies. This report is the fifth annual report produced by this project and focuses primarily on the research findings, successes and activities of 2009. Together with the four previous annual reports (2005 to 2008), it provides an overview of the progress to date of DRI research, particularly in the characterization and understanding of the recent drought over the Canadian prairies.

In the final report (coming at the end of 2010 or early 2011), the DRI community hopes to show that DRI has been an essential step towards our ultimate goals, namely:

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

2.0 Progress towards meeting the project objectives (January 2009 to December 2009)

2.1. Overview of 2009 by DRI Management (Ronald Stewart, John Pomeroy, Rick Lawford)

The year 2009 was marked by a shift from the development of new plans to the consolidation of work and plans for concluding projects and contributions to the DRI legacy by the DRI investigators. Synthesis studies have 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 of the full report. The corporate component and the Secretariat of DRI 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 forward during 2009. Investigators also have made notable research advances in Theme areas 2 and 3. In spite of this momentum, however, DRI research will be coming to an end in March 2011. In addition to providing an overview of DRI's progress in 2009, this report describes the status of DRI's phase-out plans and the development of its legacy.

Research Highlights and Theme Assessments:

During 2009, Theme 1 made excellent progress in developing a synthesized view of the drought of 1999-2005. This included filling some of the gaps in the preliminary analysis, which was initiated in 2008, as well as undertaking additional analysis to gain a better understanding of how the drought evolved. During the same period, Theme 2 provided insights into a number of processes. This new understanding was used to improve a number of hydrologic models. DRI has been particularly successful at developing an understanding of the fill and spill process and improving modeling for the progression of water from wetland to wetland in linked hydrologic 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 land-surface models. Encouraged by recent dendrochronological studies of drought by David Sauchyn and other agencies' need for a longer-term view of drought, more work has been undertaken to support Theme 4. 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 annual report documents the degree to which these activities have contributed DRI's overall goals.

Led by Dr. John Hanesiak, Theme 1 focused on the development of a synthesis of information about drought. This synthesis has brought together many different 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 of the linkages between elements such as drought indices and grain quality and the effects of data sources on values of drought indices. There are a number of sources for the data (precipitation data, for example) but not all of the data sets are fully consistent. This finding indicates that there is a need for some evaluation of the different data and reanalysis products that considers their application (e.g., different data sources for the same index could affect return periods significantly). Similarly, different indicators of surface dryness (such as growing season rainfall) emphasize different aspects of the drought. A better understanding of the strengths and weaknesses of these various indices and data products would enable DRI to inform the North American Drought Monitor (NDAM) about more efficient ways to monitor drought. Many drought indices rely on accurate precipitation data. A DRI workshop on precipitation was held at the Meteorological Services of Canada (MSC) in Downsview, Ontario in the spring of 2009. It is clear that maintaining the observational network and ensuring that high quality data are made available to users quickly and at no charge are critical requirements for both future drought studies and real-time monitoring programs.

Theme 2, which addresses the need for better process understanding, is advanced through data analysis, targeted field campaigns and experiments, and process model studies. During 2009, Theme 2 has 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 across media (land and atmosphere).

In order to develop a more comprehensive understanding of the role of land surfaces in drought, DRI held a very successful workshop on prairie hydrology in Saskatoon on November 18, 2009. The workshop, organized by Dr. John Pomeroy, dealt with three aspects of the effects of drought and climate change on prairie hydrology and prairie water availability. It attracted 80 participants and featured a rich exchange of ideas between hydrologic researchers and the user community.

Several projects study the large-scale atmospheric processes and patterns that lead to precipitation deficits on the Canadian prairies. These studies demonstrate that teleconnection patterns alone are not sufficient to understand the formation and dissipation of droughts in response to 50 KPa circulation patterns. This work focuses on the way in which the different flow regimes associated with larger teleconnection patterns control the placement of the jet stream and the upper ridge over western Canada. The PNA (Pacific North American) patterns, the strong moisture jets from the Pacific, referred to 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 trigger the redistribution of moisture through convective events (especially thunderstorms).

Studies of the interaction between surface and subsurface hydrology are central to this research. This theme includes evapotranspiration studies and the role of surface hydrology in evapotranspiration. 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 is led by Dr. Charles Lin of McGill University, also made significant progress in 2009. This progress is evident in a number of areas: assessment of model cloud outputs; ensemble approaches to ET (evapotranspiration) estimation; drought interactions with humidity fields; soil moisture feedbacks and precipitation prediction, and groundwater modelling. The work in Theme 3 includes the analysis 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 assesses the extent to which models can simulate drought and the various impacts of a drought event, and evaluates the benefits of improving parameterizations that have been calibrated or designed for drought conditions. Advances were made in evaluating and improving both atmospheric and hydrologic prediction systems through the examination of model simulations and modeling studies.

The work on model assessments included an ensemble study of the ET produced by the PAM model and a comparative study between modelled cloud outputs and the cloud cover amounts derived from the ISCCP measurements. Analytical studies have shown that although droughts influence the surrounding areas, they have a greater effect on the suppression of precipitation processes rather than lowering atmospheric moisture contents. Several models are being used to assess the influence of soil moisture on the prediction of precipitation, including VIC (Variable Infiltration Capacity), CLASS (Canadian Land Surface Scheme), and gCLASS models (gCLASS is a new version of the CLASS model).

The simulation and prediction of cloud and precipitation are central issues for drought research. A drought prediction workshop was held in Montreal in September 2009 which brought together a number of DRI experts addressing these and other drought prediction problems. Participants at this workshop scoped out an outline for a synthesis paper on drought prediction.

Work on the improvement of models has come mainly through the improved parameterizations for hydrologic models. Soil moisture studies using the VIC model and new methods of representing the non-contributing areas of the Canadian prairies are underway. Soil moisture continues to be a critical aspect of this theme, thanks to strong collaborations between DRI and a project on soil moisture assimilation in Numerical Weather Prediction Models led by Aaron Berg of the University of Guelph. Progress is also being made in simulating the interactions of groundwater and the atmosphere in areas where the high permeability of soils results in landscapes that are not conducive to producing surface run-off (areas such as the Assiniboine Delta Aquifer (ADA)). This work focuses on the development and calibration of a new version of the CLASS model, gCLASS, which will have a groundwater component and, when coupled with an atmospheric model, will provide a full suite of atmospheric and hydrologic variables.

DRI is moving toward the development of its legacy. Since one of DRI's primary objectives is to improve drought prediction, DRI needs to identify its contributions to and demonstrate its improvement of drought prediction. As noted in the Theme 3 summary, during the coming year it will be critical for DRI to identify what has been achieved in this area and which issues need to be addressed in order to fully realize improved drought prediction.

Although there is no funding for Themes 4 and 5, DRI is making a number of "best effort" contributions as well as influencing others to make progress on these research topics. Discussions are ongoing with Manitoba Hydro regarding ways in which we can gain a better understanding of how the 1999-2005 drought behaved in relation to other droughts. DRI has strengthened its collaborations with Agriculture and Agrifood Canada (AAFC) and discussed drought policy issues with provincial agencies through the Drought Early Warning System (DEWS). It has also participated in specific model development activities to improve provincial drought information services.

Secretariat update:

The Secretariat serves as the Executive arm for the project in terms of implementing decisions by the Science Committee and Board of Directors, interfacing with CFCAS (Canadian Foundation for Climate and Atmospheric Sciences), organizing and monitoring finances and deliverables, and providing many of the corporate and network functions for DRI. For example, the Network Manager organizes and summarizes actions from monthly teleconference calls of the DRI Science Committee (chaired by Ron Stewart), the Board of Directors (chaired by Jim Bruce), and PAC (Partners Advisory Committee) (chaired by Harvey Hill). The Secretariat also promotes DRI through talks and participation in external workshops and working groups, such as meetings of the Canadian GEO (Group on Earth Observations) activities, coordinates workshops, interacts with Partners and Stakeholders, and maintains and develops the website and data systems. The Secretariat's staff was relatively stable over the course of the past year. Rachael Reynen remained in her position as Financial Manager and Rick Lawford remained as the half-time DRI Network Manager. Phillip Harder and Patrice Constanza continued to serve as western and eastern data managers, respectively.

During the past year Phillip Harder and Rick Lawford prepared a proposal for the Group on Earth Observations about the DRI data legacy. The proposal was accepted as a Level 3 proposal, indicating that GEO recognizes DRI's data services and data legacy system as a contribution to the Global Earth System of Systems (GEOSS). Rick Lawford participated in a number of discussions between Canadian GEO and US GEO, where a decision to consider an assessment of the regional variability of drought indices as one of five themes for Canada/U.S. GEO collaboration. Phillip Harder led the development of DEWS, a table-top exercise for assessing 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 to request their submissions of metadata and data.

Visibility:

The annual DRI workshop, held in Regina in January 2009, was a highlight of the year. It was attended by 75 people, including a number of members of the Saskatchewan provincial government. A statement released by the workshop commenting on the future of DRI and CFCAS garnered considerable media attention. The DRI website, monthly teleconference calls, and periodic topical workshops continued to facilitate DRI communications both internally and externally. Also, the DRI program was presented in a number of meetings, generally in response to requests for invited talks. For example, talks on DRI were given by the Principal Investigators (PIs) or the Network Manager at CMOS (Canadian Meteorological and Oceanographic Society), CGU (Canadian Geophysical Union), AGU (American Geophysical Union), the IP3 (Improved Processes and Parameterisation for Prediction in Cold Regions) and WC2N (Western Canadian Cryospheric Network) science meetings, the North American Drought Monitoring meeting, a European Drought study meeting and internal DRI workshops.

Partners and Stakeholders:

During the past year, Partners continued their involvement in DRI through the Partners Advisory Committee (PAC). This committee continues to provide advice to the Board of Directors on how the project can more effectively address the needs of its stakeholders. At their meeting in Regina, the Partners recommended that a DRI Users meeting be organized. Due to provincial travel restrictions, three user meetings will be held, one in each of the three prairie provinces.

Workshops:

In addition to the annual workshop, DRI held a number of topic-specific workshops during the past year including:

- A Precipitation and Drought Indices workshop held in Downsview, Ontario in April 2009 attracted approximately 25 participants.
- The Prairies Hydrology workshop in November 2009, which was organized by John Pomeroy, attracted 80 participants. (It is described in more detail under Theme 2.)
- The DRI prediction workshop in Montreal in September 2009 which attracted a relatively small but enthusiastic group of participants.

- Although the May 2009 Research for Disaster-reduction from Extremes (REDE) Workshop was not a DRI workshop, drought featured prominently in the event and the DRI Secretariat supported the activity. It was organized by Professor Ronald Stewart with funding from the Natural Sciences and Engineering Research Council (NSERC) and attracted 50 participants from across Canada

In 2010, DRI plans to have two synthesis workshops and user workshops in each of the three prairie provinces. The synthesis workshop will support the overall DRI Synthesis, led by Ron Stewart, and an historical comparative study led by Barrie Bonsal. The series of user workshops to be held between January 2010 and April 2010 are intended to explain the research that DRI has undertaken and its application to user needs, and to find out what users would like to see included in the DRI legacy. In addition, the 5th annual DRI workshop has been planned for May 12 to 14, 2010 in Winnipeg, Manitoba.

The DRI Legacy:

During the past year DRI has made considerable progress in developing its legacy. This legacy will have four primary pillars as well as a number of other components that will preserve the rich heritage that has emerged from the DRI research and networking activities.

The four main pillars in the DRI legacy will include:

1) DRI data legacy:

This legacy involves a data system that will meet the needs of future drought researchers by providing the most comprehensive data base available on the 1999-2005 drought on the Canadian prairies. The data system will have both a centralized and distributed component so that researchers can access information from individual scientists. (Described above and in Section 4.)

2) DRI Special Issue

This special issue will consist of a number of synthesis papers, including an overall synthesis. The major synthesis articles include Prof. Ronald Stewart's overall synthesis article, Dr. John Hanesiak's drought characterization article and Dr. Barrie Bonsal's drought comparison articles.

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3) The Lecture Series

Prof. Ronald Stewart will be touring major centres across Canada to give lectures on drought, extremes and climate change. Funding for these lectures is being provided by a special grant from CFCAS.

4) The DRI Professional Document

A report, modelled after a similar publication prepared by GEO for their Ministerial Summit in 2007 and entitled *The Full Picture,* is being developed to provide a review of investigators' and collaborators' work. It will include the photos and bios for each lead contributor. This production will be a source of information for many people interested in drought research.

Other legacy activities have been completed, including the development and production of a poster on drought, and the development of statements on DRI and drought for the Wiki. Longer term legacy activities will include the development and assessment of new tools such as regional models. Contributions are also being made to other publications such as an insert on Prairie drought and DRI has been prepared by Prof. Ronald Stewart for a Canadian version of the introductory atmospheric science textbook 'Meteorology Today' by Ahrens.

Summary:

While significant advances continue to be made in each theme, the progress in Themes 1 and 2 has been directed at the deliverables and milestones proposed in the original proposal. The progress in Theme 3 has incorporated more of the hydrologic prediction activities than envisioned in the original milestones. A lot of work remains to be done on Themes 4, and 5, which have not been supported for focused study. Many aspects of these themes will have to wait for another drought study to be fully developed. The remainder of DRI efforts and resources will be directed towards finalizing the DRI legacy in 2010.

2.2 Theme Summaries

Theme 1 Summary (John Hanesiak)

Theme 1's primary objective is to quantify the physical features of the 1999-2005 drought and document the associated water and energy budgets over the region. A summary of Theme 1 activities over the past year is provided below. A journal article on Theme 1 activities has taken longer than originally planned; this was unavoidable, however, in light of the overall scope of the paper. We are now planning a summer 2010 submission, in which many of the products and analysis highlighted here will be integrated more fully. This will be part of the DRI special issue of Atmosphere-Ocean (A-O). Various DRI researchers (funded and unfunded partners) have completed critical work to quantify the extent and severity of the drought at a variety of spatial and temporal scales. Several unfunded DRI partners significantly contributed to the Theme 1 paper (integrated into the Theme 1 summary below).

The larger-scale atmospheric circulation patterns have been analyzed using a variety of gridded reanalyses data, such as the National Centers for Environmental Prediction (NCEP) and ERA40, and focus on monthly and seasonal circulation anomalies. The primary characteristics of storm tracks were frequently located either to the north or south of the prairies and possess a series of differing patterns, which each had the impact of limiting moisture transport into the region (Gyakum, Bonsal). A new finding showed that tropical surges of storm activity into the western Rockies enhances latent heat release and hence induces anomalous ridging over the mountains (Gyakum). This forces future storm tracks north of the prairies and anomalous dry spells. A comprehensive analysis of the initiation of the 1999-2004 drought, with a focus on the diabatic ridging associated with an extreme case of poleward water vapor transport, was discovered (Gyakum). Modelling studies have shown that the latent heating associated with explosive cyclogenesis in the northeast Pacific Basin is responsible for the tropopause ridging in Alaska and the Northwest Territories. This ridge drives a continental-scale descent, which is in turn responsible for the deficit of precipitation throughout the interior of North America that persisted for both September and October 1999 (Gyakum).

New ongoing analysis focuses on linkages between many drought indices and major teleconnections that affect the prairies (Bonsal and Shabbar). Results showed that moisture from the Gulf of Mexico decreased notably during the identified drought seasons. Stronger-than-normal subsidence associated with anomalously high pressure over northwestern 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. These circulation patterns over western North America and their associated moisture transport anomalies into the prairies showed some linkages to previous winter Sea Surface Temperature (SST) patterns globally and in the Pacific Ocean, where the SSTs were similar to those associated with inter-annual El Niño/Southern Oscillation (ENSO) events and ENSO-like inter-decadal North Pacific variability.

Several gridded datasets of temperature and precipitation for Canada (CANGRID) and North America (Climate Research Unit (CRU) TS 2.1) (ANUSPLIN dataset (McKenney et al. 2006)) were acquired to document near-surface meteorological characteristics of the drought (Bonsal, Hanesiak, Stewart, Wheaton). It was shown that the CANGRID and ANUSPLIN datasets were most consistent and possessed more spatial detail due to their higher resolution. Monthly maps of CANGRID and ANUSLPLIN temperature and precipitation anomalies and means have been generated and are being incorporated into the Theme 1 journal article. CANGRID precipitation revealed a distinct pattern of dry conditions; the worst was in Alberta and became less serious toward Manitoba. The variability of this pattern was marked and varied with the year and month. For example, drought conditions were most common in NE Alberta and least common in SE Manitoba.

Bonsal and Wheaton (and others) have looked at the Palmer Drought Severity Index (PDSI), the Palmer Z Index, and the Standard Precipitation Index (SPI) to spatially map the drought. These maps are also being used in the Theme 1 journal article to spatially and temporally characterize the drought. A journal article, being completed for the *Atmosphere-Ocean* (AO) special issue, includes a detailed analysis of a five-stage system for describing the evolution of droughts. Large-scale soil moisture conditions have been evaluated during the drought based on 0.5^{o} resolution water balance model data (available through the Climate Prediction Center of National Oceanic and Atmospheric Administration (NOAA)) over North America (Shabbar). Results showed that the central and western prairie moisture deficit could be linked to the northward extension of wider dry conditions in the western United States. During 2002, the soil moisture deficit worsened and spread eastward to cover the entire southern prairie provinces.

We examined summer cold low occurrences between 1980-2009 in Alberta and Saskatchewan as part of the Theme 1 drought characterization article and found there was no clear relationship between cold low occurrence and the 1999-2003 drought (Wielki & Hanesiak). Some summers in some regions of Alberta and Saskatchewan had fewer-than-normal cold lows associated with less precipitation, but this did not always occur. More analysis is required to investigate whether other drought and pluvial periods exhibited any relationship between cold lows and abnormal summer precipitation.

Heavy precipitation events are also being studied (Stewart). By some measures, such extremes were more common during the drought than expected on the basis of background climatology. It is not clear how all these major precipitating events were produced. Some are believed to have been associated with deep convection and short duration. Others are believed to be associated with stratiform precipitation and long duration. Analysis of these events is ongoing.

Estimation of prairie-wide daily crop root-zone soil moisture (RZSM) and evapotranspiration patterns using the PAM-II crop model are now possible in an “ensemble approach” based upon using various soil hydraulics and stomatal resistance terms (Hanesiak). Two journal articles have been published on this work. It has also recently been shown that negative lightning anomalies are associated with larger (>150 km diameter) dry areas (Normalized Difference Vegetation Index (NDVI) anomalies ≤ -1.0) and that these low NDVI anomaly values correspond well with plant available water (PAW) of ≤ 30% typical for crops undergoing water stress (Hanesiak). This suggests, for the first time over the cropped prairie region, a significant coupling between the surface moisture state and regional/local convection.

In addition, differences between cropped areas and urban areas have shown a mean mixing ratio difference of ~0.6 g/kg, with urban areas being drier (Strong). Summer 2009 measurements near Edmonton showed an urban heat island of ~ 3 °C together with a dry island of 2-3 g kg^{-1}. This may have significance to wet/dry boundaries in the boundary layer that can influence summer convective processes.

Analysis has shown that there was a significant reduction (compared to normal) in the number of hail and tornado events and event days during the peak of the drought. In fact, they consisted of some of the lowest counts on record (Hanesiak). This shows a link between large dry areas and the lack of severe convective weather hazards, and supports the finding described above.

A comprehensive baseline climatology of water and energy budgets for the Saskatchewan River Basin, including water and energy budgets for part of the 1999-2004 drought period, was developed from different datasets and results are published (Stewart, Szeto). The quantification and analysis of spatial and temporal variability of water and energy budgets for the prairie region, including budget anomalies during major drought episodes within the 1960-2005 periods, was completed by using reanalysis datasets. During the peak of the drought in 2001 and 2002, the region was characterized by relatively weak moisture flux convergence into the area during the winter. This resulted in reduced winter precipitation and spring snow cover. The reduced spring snow cover contributed to soil moisture deficits in the region during those two years, which were in turn linked to reduced evapotranspiration in the region during the growing season.

Annual snow cover duration (SCD) anomaly series computed over the August-July snow year from the 1972-present NOAA satellite dataset identify the 1999-2000 southern prairie (49-54N; 90-115W) snow cover season as the second shortest in the satellite record, with conditions rebounding to near-normal for the remaining drought years (Derksen). The worst years of the drought in terms of spatial extent and impact were 2001-2002, possibly signifying a lag effect from snow cover on soil moisture reserves over the region. The snow depth analysis and microwave snow water equivalent (SWE) data reveal generally negative anomalies over the southern prairies during the 1999-2000 to 2004-2005 seasons, which agree well with regionally averaged snow depth observations. The snow depth analyses and observations also identified persistent negative anomalies during the drought years across the boreal forest (54-60N; 90-115W).

Little is known about cloud climatologies during droughts. The regions with the most months with “dry” and “extremely dry” SPIs were concentrated in central Alberta and to the west of the Alberta-Saskatchewan border (Leighton, Stewart). Some other regions of the prairies had fewer than the expected number of months in these categories. Seasonally, the fall and winter periods (September to February) had more dry moths than the spring and summer seasons. There is a small but clear signal in the relationship between cloud amount anomaly and SPI, with increasingly positive SPI (wetter-than-normal conditions) being associated with positive cloud anomalies and increasingly negative values of SPI (dryer conditions) being associated with negative cloud anomalies (Leighton, Stewart). This relationship is evident in all seasons except January and February, but over snow-covered surfaces the cloud amount data must be considered less reliable. Interestingly, when stratified by cloud type, the correlation between cloud amount anomaly and SPI was greatest for high cloud.

The Variable Infiltration Capacity (VIC) land surface macroscale hydrology model was used to reconstruct 60 years (1950-2009) of daily soil moisture anomaly percentage index (SMAPI) for three soil layers over the three Canadian prairie provinces (Lin). Results show the model is a very useful tool to map and monitor drought over the prairies after taking into account the non-contributing regions. It was used to map out the major drought areas and produced patterns similar to those from other models, observations, and satellite products in Theme 1. The two major contributing factors for prairie susceptibility to drought lie in its semi-arid nature with its high variability of precipitation in time and space as well as its various soil texture/types (loss nature). These two factors were prominent in the VIC-derived variation in soil moisture (0-100 cm layer) seen in seasonal SMAPI maps.

Monthly and annual Climate Moisture Index (CMI) maps over the entire drought period have been produced and show relevant aspen growth and die-back features over the boreal zone (Hogg). Forests respond more slowly to drought than grasslands and agricultural zones. Monthly or longer time scales are therefore more appropriate to examine boreal zone drought aspects. Severe impacts on forests were recorded following the 2001-2002 drought, which triggered severe dieback and mortality of aspen (Populus tremuloides) forests across a large area of the parkland, especially between Edmonton and Saskatoon. In the most severely affected areas, 12-month precipitation amounts were <170 mm (58 per cent below normal), and CMI values indicated conditions that were the driest ever recorded in over 100 years. Biophysical monitoring at the Boreal Ecosystem Research and Monitoring Sites (BERMS) aspen site in Prince Albert National Park showed that the 2001-2002 drought led to strong (30-40%) decreases in annual evapotranspiration and gross ecosystem photosynthesis, which were associated with a parallel decrease in aspen leaf area (Barr). Although conditions were generally moist during 2003-2005, aspen mortality continued to increase during this period (Hogg et al. 2008). During and following the drought, the incidence of aspen stem damage by wood-boring insects also increased, which may partly explain this multi-year lag in drought-induced mortality (Hogg et al. 2008). Thus, unlike in agricultural croplands, the impact of this drought in forested areas has been much more apparent (dead trees and branches) in the years following the end of the drought (2003-2004 in most areas).

In addition, satellite products from the Canadian Centre for Remote Sensing (CCRS) of NDVI and NDVI anomalies have also been recently produced for use in studying drought impacts (Yang, Wang, Trichtchenko). Intercomparisons of all of the these products will be undertaken in the near future to examine similarities and differences with other products and highlight the spatial temporal patterns of the drought over large scales.

Work has been completed on compiling the final years of agricultural drought index and wheat yield data (Bullock). The goal was to identify those indices with the strongest correlation to wheat yield and quality, then use the indices to quantify drought extent and intensity in Western Canada over the entire drought period. Indices based on evaporative demand and water balance (supply *v*. demand) were more strongly correlated to wheat yield and quality than indices based on water supply (precipitation) or crop water use. Thus, common meteorological drought indices such as the percentage of Normal Precipitation Index (NPI) and SPI are not the best choice to reflect agriculture drought impacts. In addition, ten-day composite Moderate

Resolution Imaging Spectroradiometer (MODIS) NDVI data from the late June to late July period provides a good indication of census region yields (Bullock). A manuscript has been prepared for submission for publication with co-authors from the Canada Centre for Remote Sensing (CCRS), who provided the MODIS data.

A detailed description of the drought that occurred within the St. Denis National.Wildlife Area in Saskatchewan is currently being prepared (Pomeroy). Reliable datasets of incoming solar radiation, temperature, humidity, wind speed, precipitation, soil moisture, snow pack water equivalent and pond level were assembled for St. Denis from 1999 to 2006 to show the drought and post-drought recovery period. A number of other datasets, including station data and reanalyses products for use in the Cold Region Hydrological Model (CRHM) platform, are being used to characterize the drought over larger spatial scales. A stream basin model has also been developed and has been run for the 1961-1990 normal period for Winnipeg as a test site (Pomeroy). The SWE computed for fallow fields varied tremendously from year to year, but the mean SWE values show the large reduction in SWE during the drought years, even at Winnipeg, which was less affected by the drought than regions further to the west. The CHRM and stream basin models will be used over a prairie wide basis in future work.

Lawford and Harder prepared an analysis of streamflow data (actual and naturalized flows) on the prairies from 1999 to 2005. Results suggest that small basins respond more quickly and may be more susceptible to drought than large basins. In some cases, the rivers in smaller basins go completely dry during drought conditions. Naturalized flows generally reflect the progress of the drought along the Alberta-Saskatchewan and Saskatchewan-Manitoba borders, although some significant deviations occurred at specific stations. It is important that those who make decisions based on naturalized flows are aware of these differences, especially when providing interpretations of data in support of provincial agreements. While small rain events do not have a measurable impact on the flows, larger-scale, heavy-rain events can result in significant increases in monthly flows. These above average values can last for a month or more at some locations.

The picture that emerges from this analysis in terms of drought is that although the basins were dry in southern Alberta, they consist of small tributaries that are frequently dry in summer.

In 2001 and 2002 in particular, the flows in the North and South Saskatchewan were below the ten-percentile values. These anomalies appeared to propagate downstream to the Manitoba-Saskatchewan border. With the exception of short-term events associated with local storm systems, this hydrologic drought became significant again in 2003 and early 2004 on both the Alberta-Saskatchewan and Saskatchewan-Manitoba borders.

Some ground water observations have been collected and trends have also been identified. A survey by the Alberta Environment Groundwater Observation Well Network (GOWN) indicated that the groundwater level was steadily decreasing in some regions due to over-pumping (this conclusion was proved this past year). The effects were particularly pronounced during the drought. This confirms the need for an integrated approach rather than using well hydraulics alone, considering the anthropogenic effects as well as meteorological forcing in the water management during drought. Hence, a detailed study examining the relation between groundwater level, water usage, and meteorological forcing in southern Alberta is still progressing. The analysis of groundwater level recorded in the West Nose Creek watershed indicated that the recovery of water level from the 1999-2002 drought took two to three years. Similar ground water observations have been obtained in the last year for the Assiniboine Delta Aquifer (ADA) in Manitoba and work is ongoing to identify any trends that may have occurred during the last drought period. Other shallow and deeper water well data from various regions in Alberta, Saskatchewan, and Manitoba have been gathered and stored as monthly averages. Preliminary analysis showed that shallow wells were noticeably depleted during the drought and recovered shortly after. Deeper wells, however, respond over much longer time scales and can be used to gauge longer climatological signals over large areas. The deeper well data are currently being compared to the Gravity Recovery and Climate Experiment GRACE satellite estimates of total water content during the drought to validate GRACE observations.

The remote sensing observations of gravity from the GRACE satellite system can be translated into monthly measurements of land surface moisture stored within the Saskatchewan River Basin. The GRACE satellite measurements provide an integrated quantity of land surface moisture at continental scales and are compared with the monthly water balance developed from an atmospheric P-E analysis obtained from the four times per day global analysis from the

Canadian GEM. Both model estimates and observational data of moisture during the drought period are represented by a reduction in moisture of approximately 6 cm water equivalent during the fall of 2003 (averaged over the entire Saskatchewan River Basin (SRB). Beyond the fall of 2003, moisture in the basin recovered through 2004 with a cycle of drying and wetting and steadier conditions in 2005. This period corresponds with the end of the drought period and widespread flooding in the Canadian prairies during the spring of 2005. Similar GRACE measurements have been downscaled to the ADA region and results show that ground water observations and gravity anomalies were correlated during most of the record. Not all wells show this behaviour, which indicates that the local influences on the regional water balance are not all captured by GRACE. GRACE's downscaling results to well observations correlated to a high of R=0.8 to a low of R=0.5. In addition, gravity results from the GRACE satellite do not appear to have the same dynamic range of the individual lysimeter data.

Extensive composite data sets have been constructed by John Pomeroy and Kevin Shook for fifteen locations throughout Alberta, Saskatchewan, and Manitoba, in order to develop and validate the Cold Regions Hydrological Model (CRHM). These data sets, which include computed data for solar radiation as well as measured data for other variables at the hourly time scale, could support drought characterization studies. Brenda Toth (HAL) and Anthony Liu continue to provide support on data and modeling activities for DRI.

Theme 2 Summary (Masaki Hayashi)

The overall objective for Theme 2 is to improve the understanding of the processes and feedbacks governing the formation, evolution, cessation, and structure of the drought.

Milestones for Year 1-5

Theme 2 milestones for Year 5 were met as the focus shifted from data-gathering to the analysis and synthesis phase. In general, data has been acquired from field observations, collaborating agencies, or data rescue, in some cases. Model evaluations hypothesis development and testing have been undertaken and conclusions are being reached about model sensitivity and the relative importance of various processes. The focus has been on completion of data analysis, concluding model runs, and preparing and submitting journal papers to describe the results.

Progress Summary

The following summary is organized according to the spatial scale from continental-scale atmospheric processes to plot-scale hydrological processes. To discover the atmospheric circulation regimes that are particularly pertinent to droughts in North America, we have conducted theoretical studies of blocking using the NCEP's global reanalysis data and North American Regional Reanalysis (NARR) data. Many previous droughts in central and Western Canada have been associated with the positive phase of the PNA pattern index, as the positive PNA phase is associated with anomalous mid- and upper-tropospheric ridging in Western Canada. Our study has identified a significant trend in the PNA index toward positive values of the past 50 years. The precipitation deficits at several locations, however, are not correlated with any of the established teleconnection indices such as the PNA and the ENSO. Therefore, we are analyzing the different flow regimes that contributed to the length and severity of the recent Prairies drought: northward-shifted jet stream and storm track; western British Columbia meridionally-oriented ridge/trough couplet; and the positive phase of the PNA. In addition, we are conducting detailed analysis of circulation anomalies at multiple scales to find correlation between the beginning of the 1999-2004 drought and circulation anomalies including the explosive cyclogenesis in the Gulf of Alaska.

In order to improve our understanding of the processes and feedbacks governing the properties of a drought, we tested the Canadian Regional Climate Model (CRCM) with respect to cloud-precipitation relationships. Compared to the observational results, the CRCM does very well in reproducing the average annual cycle of precipitation averaged over the years 1961-2004, but differences in individual years are typically of the order of 5 per cent. When the SPI was compared, the model produced fewer dry months ($SPI < -0.5$) in the period 1999-2004 than were observed, but the spatial distribution of severest precipitation deficits from the model was in agreement with observations. Average annual cloud amounts are about 10 per cent greater than observed, but the agreement is somewhat better in spring and summer. Mean cloud amount anomalies are negative during drought periods and positive during wet periods. The relationship between mean cloud anomaly and SPI was stronger in the model output than what was gathered from the observations. As expected, the mean top-of-atmosphere (TOA) albedo from the model agreed more closely with the observations than did cloud amount.

On a smaller scale, we examined the flow of atmospheric water through clouds and precipitating systems to the surface within and adjacent to the drought regions, focusing particularly on episodic events. Key issues include the relative contributions of water vapour from external and local moisture sources, the efficiency through which cloud systems convert this water vapour to precipitation, the possible role of the drought environment in enhancing the strength and/or efficiency of precipitating systems, and the production of scattered partially drought-alleviating precipitation. A detailed analysis of the occurrence of virga was carried out for the summer months of 1999-2005 using the sounding data near Edmonton and radar data in the vicinity of Calgary, Edmonton, and Saskatoon. The virga was sometimes more prevalent over these sites than precipitation at the surface. In addition, the average cloud base temperature during virga events was $< 0°C$, implying that sublimation of particles initially occurred instead of evaporation. This generally means a more rapid mass loss, thereby promoting dry conditions at the surface. A several year-long effort to study the June 2002 major rainstorm, which changed extremely dry conditions over the southern prairies to above average, has largely been completed. A key finding is that the storm was actually made more intense because of the dry sub-cloud region presented in drought that facilitated rapid evaporation of falling precipitation and this in turn altered storm dynamics. Studies of other instances of heavy precipitation during the drought showed that such extremes were more common during the drought than expected on the basis of background climatology.

Convective processes related to storms were investigated over the Alberta foothills during the 2008 UNSTABLE experiment using mobile transects across drylines (i.e. summer Chinook effect). Multiple transects across drylines revealed moisture gradients varying from 15 to 50 g kg^{-1} km^{-1}, representing virtual discontinuities in the atmosphere never previously documented in

Canada. A link (or physical analogy) with drought was suspected through reanalysis of the Pine Lake tornado of July 14, 2000. This storm was very typical of severe Alberta storms: it initiated on the east slopes of the foothills and was aided by moisture provided through daily evapotranspiration from grain crops over the plains. This moisture converged over the foothills following lee cyclogenesis over southeast Alberta, with a subsequent dryline from the mountains helping in the convergence and storm initiation. The potential link to drought follows from the intensification of this storm over central Alberta, hypothesized to result from dry air over drought-stricken southeast Alberta converging with moist air ahead of the storm. The Pine Lake storm case in relation to the drought region is being evaluated further using radar and satellite data.

DRI Investigators analyzed the occurrence of severe hail and tornado events and lightning over the prairies during the drought period. There was a significant reduction from normal in the number of hail and tornado events during the peak of the drought, clearly showing the link between large dry areas and the lack of severe convective weather hazards. Over the 1999-2008 period, lightning counts were lowest in 2002 and lightning activity was more variable during the drought period than during the post-drought period over the boreal and grassland eco-zones. We used the Canadian Prairie Agrometeorological (PAMII) crop model to examine in more detail convective activity in association with wet/dry areas. The model accuracy was investigated using the daily evaporation flux derived by eddy covariance systems. The data analysis has demonstrated that PAMII is skillful at modeling the day-to-day variability in evaporation; PAMII is capable of capturing the difference in evaporation above two contrasting vegetation types; and PAMII simulates the contrasting evaporation observed in wet versus dry years.

The response of evaporative fluxes to variability in soil moisture and groundwater conditions was examined at instrumented study sites in Saskatchewan and Alberta. Such studies improve understanding of land-atmosphere exchange processes and the response of hydrological conditions to a drought. Evaporative fluxes were monitored simultaneously on two land covers (perennial grass and barley) in the West Nose Creek watershed near Calgary from April to October 2009. The data are being analyzed to differentiate the characteristics of different vegetation types and provide calibration data for numerical models. At several study sites in

Saskatchewan, data from the deep geological weighing lysimeter wells are being used to improve the way distributed hydrological models characterize moisture budgets. Particularly of concern is how well the models simulate evapotranspiration during the drought when soil moisture stress is extreme and deep-rooted vegetation tends to draw on deeper groundwater stores. Water and energy flux data from the BERMS/Fluxnet forest and grassland sites are being compared with particular emphasis on water and energy fluxes during the drought years. Grassland fluxes responded more strongly to drought conditions than forest fluxes. Data from the BERMS fen site indicated that evaporation losses from the fen during the last year of the drought (2003) were not significantly lower than in the following very wet years, but net carbon uptake was minimal in 2003.

A new approach has been developed for deriving distributed estimates of the mean daily net radiation balance needed for parameterising energy balance and combination evaporation models. The method has been demonstrated and applied for the calculation of evaporation from a grassed surface at a complex parkland site in central Saskatchewan.

The processes governing hydrology in an area with a variable contribution area has been examined through extensive field work in the St. Denis area, a hummocky terrain characterized by potholes that episodically contribute to stream flow. Al Pietroniro and Dean Smith have used both summer and winter measurements to develop a model that simulates the transfer of water from wetland to wetland in this area. Continued work on modelling of the Assiniboine River Basin upstream of the Kamsack outlet will contribute to improved hydrological models and to a better understanding of the response of runoff in this basin to drought conditions.

Overall, significant progress was made toward 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. The investigators are expected to continue with the development of the final model in conjunction with Theme 3.

Theme 3 Summary (Charles Lin):

Theme 3 has made significant progress toward achieving the objective of assessing and reducing uncertainties in the prediction of drought and its structure during the past year. A major activity in the final year of the CFCAS grant period is to synthesize the results in a prediction paper and to contribute to other DRI synthesis papers.

The utility of a multi-model ensemble approach to quantify the uncertainty in modelled ET and root-zone soil moisture was investigated by Hanesiak and his colleagues. 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.

The flow of water through clouds and precipitating systems to the surface in and adjacent to drought regions has been analyzed by Stewart. He examined sounding information from Edmonton before and during drought episodes, which showed that integrated water vapour amounts can be near normal even during the worst parts of a drought. This is contrary to simple concepts of decreased water vapour during droughts.

Cloud-precipitation relationships from the CRCM with those from observations over the prairies have been undertaken by Leighton. Different statistics were evaluated, including annual precipitation, cloud cover, top-of-the-atmosphere albedo, and SPI index. The CRCM generally performs well, with varying degrees of success for different parameters.

Lin continues work on coupling of atmospheric and hydrological models for flood forecasting, soil moisture simulations, and drought monitoring. The VIC model has been used to reconstruct soil moisture over the prairies over the period 1971-2005 with a spatial resolution of 30 km. SMAPII was 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 at (www.meteo.mcgill.ca/~leiwen/vic/prairies).

DRI modelling tools are being developed into community-based models that will be accessible to a variety of researchers across the country. WATFLOOD, WATCLASS and CLASS are being combined to create MEC (Modélisation Environnementale Communautaire), along with a surface hydrology component (MESH). Other initiatives have also been initiated with CLASS. The first collaboration began with Aaron Berg of Guelph University and focuses on driving CLASS for the 1997-2007 period over the prairies. The 11-year CLASS soil moisture simulation is now complete. The second initiative is being conducted with Alan Woodbury. Lin et al. set up gCLASS, a groundwater version of CLASS developed by Woodbury's group, to run over the Athabasca Basin. Dr. Woodbury assessed the applicability and viability of the model's code by using an improved version of the Canadian Land Surface Scheme CLASS, (or SABAE-HW; Soil Atmosphere Boundary, Accurate Evaluations of Heat and Water) along with BOREAS data and carrying out intercomparisons with the SHAW, CLASS, HYDRUS-1D and HELP3 models. These efforts support the long-term goal of developing an efficient coupling of the Canadian land surface scheme with groundwater flow model.

Snow melt is a critical source of spring moisture over the DRI study area. A test of the distributed and aggregated modelling strategies for blowing snow transport and sublimation was conducted at the St. Denis National Wildlife Area in Saskatchewan, Canada. Spatially distributed estimates of seasonal blowing snow transport and sublimation for 6 m × 6 m grid cells were calculated and aggregated to seven landscape units that represented the major influences of surface roughness, topography and fetch on blowing snow transport and sublimation. Both the distributed and aggregated simulations predicted similar end of winter snow water equivalent and agreed well with snow survey observations. In addition, the CRHM model has been completed and run for the period 1960-2005

Basins are being simulated at multiple scales. In particular the hydrology of Saskatchewan River Basin is being simulated using a MESH prototype at a resolution of 15 km and smaller basins with CRHM at a resolution of 1 km. In addition, WATFLOOD to estimate daily naturalized streamflow for 1990 – 2005 at 13 nodes across the SSRB. The roles of various storage mechanisms in the basin including groundwater and glaciers have also been examined.

Modelling the ‘fill and spill’ of depressions (wetlands) in the landscape, using current methods, has 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 prairie are underway.

Theme 4 Summary (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.” Research done by Bonsal has helped scientists to understand the atmospheric and oceanic variability associated with previous droughts and pluvials on the prairies.

Barrie Bonsal and his colleagues examined previous droughts that match or surpass the severity and extent indicated by both the PDSI and SPI indices for the 1999-2005 drought. Some of these drought years include 1929, 1931, 1961, and 1988. They have been looking for similarities in formation, migration, and termination by applying a five-stage framework to each drought and examining how each stage progresses in comparison to our focus drought. So far, results have shown that these stages can be identified in other major droughts. Because of this, we are able to assess similarities between these droughts and the 1999-2005 drought. Once completed, this investigation will provide a better understanding of droughts and help improve preparation, coping mechanisms, and perhaps even forecasting for future droughts.

John Hanesiak and his colleagues have studied extended historical severe weather (hail and tornadoes), lightning, and cold low datasets. In addition, Lisa Hryciw is currently completing her M.Sc. thesis on the historical perspective of drought across Canada ranging from 1948 to the 1999-2005 drought.

Other work has contributed to the characterization of this recent drought in terms of its historical variability. We have correlated seasonal teleconnection index values of the Southern Oscillation Index (SOI), Pacific Decadal Oscillation (PDO), PNA, AMO, Arctic Oscillation (AO), and North Atlantic Oscillation (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. Preliminary results indicate several significant relationships between the drought indices and individual teleconnections, such as the PDO and PNA. These findings have helped understand the large-scale circulation patterns and teleconnections associated with both the 1999-2005 drought and previous droughts on the prairies.

DRI studies have examined the relationship between precipitation and clouds over the prairies for the 20-year period (1984 to 2004) using data from the ISCCP SRB datasets. DRI investigators studied the details of secular changes in atmospheric circulation regimes as well as other atmospheric circulation anomalies over the past 60 years. This is a first step toward a deeper understanding of the associated drought structures during the 1999-2005 drought as they compare to historical major drought episodes.

We examined hydrometeorological extremes from historical time series of temperature and precipitation from high-quality datasets with over 100 years duration. Results indicate that these extremes are weakly multi-fractal over periods shorter than one month, which 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.

Dr. Garth van der Kamp has compiled region-wide observation well data observations over 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.

Theme 5 (Elaine Wheaton)

DRI supports this theme in a broad way through its Partner Advisory Committee, which enables stakeholders and user communities to have more input into the decision process. During the past year the DEWS exercises also helped engage users in discussions about DRI outputs. A number of DRI projects have produced results that support the goals of Theme 5, although this is not the major objective of any of these research projects. 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 (Toth et al, 2009) and with water use in the South Saskatchewan River basin (Bruneau et al, 2009).

There is a clear relationship between DRI's overall objective and this theme's primary objective: both benefit from a better understanding and prediction of Canadian prairie droughts. Many of the researchers work with partners; these linkages benefit each partner's work and collectively benefit society. Information on drought is useful to the design of sustainable resource management strategies and the development of drought warning strategies. For example, the Cold Regions Hydrological Model's research will provide information for sustainable water management. Another example is the improved understanding of groundwater resource dynamics, which benefits the many users of this vital resource. Examples of products from this work are listed in the publications section of this report. These publications document lessons learned from the characteristics, impacts of, and adaptations to this recent major drought, as well as community case studies regarding water scarcity and institutions' role in drought response.

There is also evidence that provincial interest in DRI information assists drought adaptation. For example, Paul Bullock has been invited to work with a provincial/state government initiative on agricultural adaptation strategies and meetings are scheduled for March 2010. Similar user interactions arose from several other University of Manitoba studies involving estimates surface evapotranspiration, assessments of irrigation demand, and simulations of streamflow over the Churchill River Basin in Manitoba.

2.3. Participation of government, university, and foreign researchers in DRI.

The work of co-investigators is being integrated into DRI projects primarily through the development of synthesis reports. Three synthesis reports are envisioned: one dealing with drought characterization, a second dealing with prediction, and this Annual Report, which provides a synthesis of the overall knowledge developed during the project.

Results are also being integrated across space and time scales. Large-scale planetary circulations by Barrie Bonsal are being integrated with the results of those researchers who examine atmospheric physical processes and feedbacks at smaller spatial scales. (Kit Szeto, Ron Stewart). This will provide a better overall depiction of the physical features of this drought at a variety of scales and thus aid in the better understanding of the processes and feedbacks acting on these scales.

Many of the contacts between investigators took place at the annual DRI workshop. The workshop provided briefings on the work of each scientist and allowed for substantial interaction between scientists. By focusing events on specific aspects of the drought, DRI has opened up many opportunities for collaboration (sharing data sets and joint investigations). Students were frequently co-supervised on projects that contributed to several investigators' own research projects. Masaki Hayashi and Al Pietroniro have been collaborating with John Pomeroy as they transfer techniques from his CRHM model to the Versatile Soil Moisture and MESH Models.

Collaborations include work by Profs. Ronald Stewart and Henry Leighton on drought, clouds and radiation. Ronald Stewart and Kit Szeto are also working on the June 2002 storm analysis, and Ronald Stewart and John Hanesiak have worked on other major precipitation events. The following DRI collaborators have contributed to the Theme 1 article thus far: A.G. Barr, T.A. Black, R. Brown, C. Derksen, L.B. Flanagan, T. Hogg, B. Kochtubajda, Y. Luo , J.H. McCaughey, A. Shabbar, A. Trishchenko, S. Wang, C. Wielki, Y. Yang, and T. Zha.

Drs. Geoff Strong and John Hanesiak collaborated on the analysis of 2008 UNSTABLE field work to examine drought-processes in Alberta. John Hanesiak and Rick Raddatz have produced an ongoing crop phenology model output and maintain discussions related to the PAM model. These efforts will include the preparation of several joint papers. Collaborations are also ongoing between John Hanesiak, Paul Bullock and Masaki Hayashi through shared results and information. John Hanesiak has been communicating with all DRI investigators and collaborators toward the Theme 1 characterization article. Henry Leighton collaborated with Alexander Trichtchenko and Alexander Radkevitch of CCRS regarding satellite data.

Drs. Charles Lin and Jacques Derome (McGill University) collaborated on a seasonal forecast project using Climate Variability and Predictability (CLIVAR). Derome and Lin are also the co-supervisors of M.Sc. student Rabah Aider, who completed his thesis in December 2008. His work consists of an analysis of the skill of monthly and seasonal forecasts using GCM3. Charles Lin collaborates with Alan Woodbury to run his groundwater model (gCLASS) for the Assiniboine Delta Aquifer. Dr. Lin is co-authoring a paper with John Pomeroy on the reconstruction of 60 years (1950-2009) of daily soil moisture over the Canadian prairies using the VIC model. He is a co-PI in a project led by Aaron Berg of the University of Guelph on a CFCAS-funded grant to use CLASS in a stand-alone mode for soil moisture analysis.

Dr. John Gyakum is collaborating with Hai Lin of Environment Canada. Together they aim to determine how model bias in precipitation and temperature forecast can be reduced. Dr. Al Woodbury has been interacting with Manitoba Water Stewardship staff in carrying out the ADA studies. Dr. Al Pietroniro works closely with the HAL laboratory and the University of Saskatchewan to ensure coordination between DRI, NAESI and Hydrological modelling activities. Drs. Ken Snelgrove and Garth van der Kamp have collaborated on a comparison of the geological weighing lysimeters with the gravity returns from the GRACE satellite system and hydrological models run during the drought period.

Future collaborations will be developed to examine the impacts of storms and other elements of drought (Elaine Wheaton), while other research relationships will be developed as part of the overall DRI synthesis (Barrie Bonsal and Amir Shabbar). Ronald Stewart is also having initial collaboration with researchers in the U.S. as well as in other countries through WCRP/GEWEX/CEOP which are expected to increase as that program matures.

2.4. Contributions of government scientists and experts to DRI

A number of government scientists are collaborators in DRI. Most notable in terms of substantive contributions are Dr. Kit Szeto and Amir Shabbar, both from Downsview, ON. A number of projects are being carried out in collaboration with federal scientists; some are even led by federal scientists. Studies on drought processes have been advanced through Barrie Bonsal's collaboration with Amir Shabbar and Kit Szeto of Environment Canada in Toronto, ON. Elaine Wheaton has engaged with Dan McKenney and Ted Hogg of Canadian Forest Service and Grace Koshida (Environment Canada) in her impacts studies. Anne Walker and Chris Derksen from Environment Canada's Climate Research Branch provided John Hanesiak's drought characterization project with SWE data from SSM/I. Both Eyad Atallah and John Gyakum regularly communicate with Environment Canada scientists, Marco Carrera and Ron McTaggart-Cowan, concerning modelling issues and the appropriate means of conveying climatological information.

A number of collaborations have taken place between scientists in Western Canada. Dr. Geoff Strong has a continuing collaboration with Craig Smith of Environment Canada in Saskatoon, SK. He has provided instrumentation for conducting surface mobile transects since 2004 and coordinated the instrumentation of towers at Kenaston in 2009. He worked with Neil Taylor of Environment Canada (Edmonton, AB), Craig Smith (Saskatoon, SK), and Dave Sills (Toronto, ON) on the UNSTABLE dryline study. They also collaborate with other academic investigators. Dr. John Hanesiak has acquired lightning data from Bob Kochtubajda and Bill Burrows using HAL (this required a users' agreement). John Hanesiak and Bob Kochtubajda collaborated directly in order to provide the lightning analysis for the Theme 1 article. Bill Burrows collaborated with Julian Brimlow recently, and completed extensive programming to assist Brimlow's analysis.

Agriculture and Agrifood Canada (AAFC) have provided access to their model output, precipitation anomaly data, and drought indices data for drought characterization studies by John Hanesiak. Ronald Stewart is working with Environment Canada colleagues in Winnipeg, Toronto and Edmonton to acquire and analyze data and model outputs. Environment Canada staff (Hai Lin, Peter Houtekamer, Juan Sebastien Fontecila, and Yufei Zhu) provided Charles Lin with the data needed to drive VIC model. Dr. Lin is in contact with Trevor Hadwen's group in Agriculture and Agri-Food Canada (AAFC) on the North American Drought Monitor. He also maintained our established linkages with Eric Wood (Princeton University) and Dennis Lettenmaier (University of Washington) for using VIC over Canada.

Scientists from the Canada Centre for Remote Sensing provided satellite data and data products to Henry Leighton (Drs Trichtcheno and Radkevitch) and to Paul Bullock (Dr. Shusen Wang). These data sets included ten-day composite MODIS NDVI images for analysis. Scientists from CCRS also worked with Shammi Raj and Paul Bullock to develop a manuscript on their research and on meteorological datasets for Western Canada.

DRI has also involved collaboration with provincial government departments. Masaki Hayashi worked with Daniel Itenfisu from Alberta Agriculture and Rural Department to improve the soil moisture model , which the province applies to its drought assessments for insurance programs. Ralph Write (Alberta Agriculture) provided all of his micrometeorological data to John Hanesiak's study. Provincial groundwater agencies continue to cooperate with Garth van der Kamp's study by sending him the necessary observation well data and helping to select the appropriate wells. They will also help with characterizing the hydrogeological setting of each well. In turn, they will receive the compiled data for the prairie region and, of course, the results of the drought-related analysis. At the municipality level, the groundwater monitoring methodology developed in the West Nose Creek study has been adopted by the Municipal District (MD) of Rocky View for the MD-scale monitoring of groundwater.

2.5. Plans for the final nine months of DRI Research.

During 2010, all investigators will focus their energies on completing their analysis and preparing reports and publications. A number of DRI scientists are contributing to journal articles and legacy documents such as the DRI Special issue and the DRI Professional document.

Barrie Bonsal will be completing his analysis and synthesizing them for journal articles, including in the special DRI issue of *Atmosphere-Ocean*. Elaine Wheaton will also be synthesizing her results on a drought development characterization scheme in a journal article for the special DRI issue of *Atmosphere-Ocean*. The Theme 1 and Theme 3 synthesis articles will directly contribute to the goals of DRI as well as the DRI legacy.

Since DRI is coming to a close in September 2010, some of the newer ideas for drought research are unlikely to be realized. DRI scientists will have to wait for a future drought project to bring these ideas to maturity. Future work will help improve the planning and preparation involved in coping with droughts by developing an improved ability to identify the different stages of drought, starting with the onset. A next goal will be to relate these indices with observed drought impacts, including but not limited to impacts of variables such as pasture growth, water levels (dugouts), and aerosols (dust storms). These comparisons will provide an indication of the usefulness and applicability of drought indices.

A number of investigators plan to advance their process studies for a final season by collecting special data sets and finalizing their analyses. Masaki Hayashi will continue to conduct process studies and data analysis at the West Nose Creek watershed (Theme 2), further improve the Versatile Soil Moisture Budget (VSMB) (Theme 3), and start coupling it with a groundwater flow model. Geoff Strong plans to finalize the analysis of the Kenaston vertical profile data over crop/grass in the early part of 2010. He will also complete the Pine Lake drought/dryline comparison and other transect data. John Hanesiak and Julian Brimelow will continue to identify wet/dry soil moisture and ET areas using the PAM-II crop model and NDVI over the prairie-wide region. They will link these areas to deep convection/lightning and will examine specific case studies of cloud development along the wet-dry boundaries during the drought. They will be aided by collaborations with Rick Raddatz, Bill Burrows, and Geoff Strong.

Studies on the validation of CCRM results using SRB data and the historical perspective of the 1999-2004 drought will be published. DRI studies will also document the synoptic-scale forcings driving this drought. At least one refereed publication will be produced from the supervised M.Sc. thesis.

DRI research has established the essential foundation for a significantly improved understanding of the 1999-2004 prairie drought. John Gyakum will build upon this foundation with continuing detailed synoptic analyses of vertical motions and moisture budget analyses associated with the generation, maintenance, and decay of the relevant circulation regimes associated with the various components of the drought. Dr. Gyakum is building upon work recently completed by Roberge et al (2009) on moisture transports, particularly the “Pineapple Express,” to focus on the effects of strong latent heat release on diabatic ridging and the displacement of the mean jet to the north of the drought region. He intends to continue his research on the relationship between the secular changes in atmospheric circulation regimes, regional climate change, and the associated phenomena of droughts.

DRI will continue its work on the improvement of drought prediction by further analysis of the seasonal forecast runs using GCM3 as part of the Historical Forecast Project (HFP). The results show low skill in the seasonal forecast of drought events in the prairies. In the HFP experiments, sea surface temperature anomalies are the main lower boundary forcing, with the soil moisture being initialized using climatological values. Charles Lin will examine the role of soil moisture initialization in seasonal drought prediction. Using more accurate soil moisture information in the initial conditions could lead to improvement in the forecast skill.

Based on the overall goals for DRI, Al Pietroniro will focus his work on improving the understanding of the large scale setting of drought; the understanding of surface-atmosphere feedbacks of energy and water, and improving the understanding of ET at various scales from prairie land and water surfaces. Through the work of John Gykaum, DRI will continue to monitor the details of GPS-derived precipitable water to provide crucial sub-synoptic-scale information. This will enhance our understanding of evapotranspiration’s impact on available atmospheric moisture/stability, especially since numerical predictions of ET in operational models are somewhat problematic.

Al Woodbury will continue to validate the gCLASS code with Boreas data and with 3- and 10-year runs. Al Piertroniro plans to continue with the MESH simulations at the Kenaston site until he has a 50-year simulation. Ken Snelgrove has launched a new project to assess the "memory" of deep soil on seasonal predictability of the climate system, including drought.

Plans to use the large 3-D ParFlow model have been abandoned because it appears that the computer resources are not adequate to allow the model to be run over the domains sizes used by atmospheric modellers.

3.0 Impact

3.1 Recently achieved short and medium term objectives:

Most of the short- and medium-term DRI objectives have been achieved. A number of deliverables have been produced over the course of the past year, including the initiation of synthesis projects related to drought processes in the 1999-2005 drought and the characterization of drought and drought prediction; clarification of the need and opportunities for a drought data legacy; and preparation of other DRI legacies including a special *AO* issue and DRI Professional document.

The efforts of individual investigators have contributed to these overall goals. They include the completion of analyses of maps of various drought indices that have been a major contribution to the drought characterization study (Barrie Bonsal, Elaine Wheaton). The completion of many maps and data sets for inclusion in the DRI data legacy include maps of the North American Prairie Region (Elaine Wheaton). Each drought year is compared to the 1999-2005 drought. Maps of multiple time series, including yearly and drought specific showing the percentage of grids in severe drought, have also been drawn up, in addition to isoline maps showing the outline of the severe drought based on our five stage plan and a series of weekly meteorological parameters for Western Canada over the period 2000 to 2004 (Paul Bullock). A comparative analysis of gridded climate and drought data with observed station data that permits improved selection of such databases in drought studies was also mapped (Elaine Wheaton).

The understanding of many drought processes has been enhanced and the results have been published during the past year. Publications addressing the processes governing the exchange of water and energy between the soil and atmosphere and their effects on groundwater have been prepared. This new understanding is being incorporated in a groundwater recharge model (Masaki Hayashi). Geoff Strong quantified the relative importance of daily evapotranspiration from grain crops and urban dry islands for cities of five to 500,000 in terms of thunderstorm initiation for a range of situations, while John Hanesiak used ensemble approaches to modeling/predicting soil moisture and ET under various soil and vegetation regimes. The PAMII model has been upgraded and its ability to simulate ET over different vegetation and contrasting growing seasons has also been validated by John Hanesiak. Paul Bullock gathered results for a series of tests of meteorological-based agricultural drought indices and their relationship to observed field data showing grain properties. Al Woodbury engaged a number of experts with their own models in intercomparison studies with the gCLASS model.

MODIS NDVI data has been tested against census agricultural region yields of 4 major crops in western Canada and shown to provide a reliable means for quantifying yield. The importance of marginal precipitation, the occurrence of major storm systems, and cold season features have all been studied in the context of the 1999-2005 drought. Studies addressing the effect of these processes on drought structure and evolution will now be undertaken as part of the DRI synthesis.

A comprehensive hydrological model has been developed by John Pomeroy that contains physically based blowing snow, snowmelt, infiltration to frozen soils, infiltration to non-frozen soils, evapotranspiration and runoff processes. 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.

Another project, which is underway and is expected to yield results before the end of DRI research in September 2010, is an analysis of the skill of seasonal forecasts of drought by the Canadian operational or research models. In addition, studies of the role of soil moisture initialization in seasonal predictability will be undertaken using outputs from the VIC, CLASS and gCLASS models.

Our next goal is to focus on specific drought years for further comparison involving drought characteristics and to draw conclusions about similarities and differences among the droughts. The majority of the analyses have been completed and work is well underway toward the aforementioned synthesis of results into a journal article.

3.2 Significance / impact of the results achieved to date

Contributions to government policy

The project has had an impact on the development of federal, provincial, and municipal governments' policies. The Municipality of Rocky View adopted the implementation of a locally-based groundwater monitoring network designed by Masaki Hayashi for the West Nose Creek pilot study. Masaki Hayashi also is working with Alberta Agriculture Resource Directorate to improve the VSMB model, which is used operationally in crop insurance decisions.

As a result of Dr. Woodbury's research results, the significant risk to water quality from the nutrient management activities in Manitoba have raised concerns with the provincial government which has placed provincial moratoriums on the expansion of livestock enterprises and a regulatory framework is being developed for nutrient management. Results from the CHRM model 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.

Manitoba Agriculture, Food and Rural Initiatives invited Paul Bullock to be part of a multi-provincial/state initiative on the development of agricultural adaptation strategies for climate change in 2010.

DRI addresses fundamental issues pertaining to drought. Issues such as marginal precipitation occurrence and individual storm events do not seem to have been examined in detail before within the context of drought. This research constitutes a new field of discovery for students because it addresses key aspects of a type of hazardous weather that has not been studied before.

Studies on drought indicators will improve the quality of analysis undertaken with the support of either Canadian or North American drought monitoring products. Since government programmes are based on these indices, better information should lead to better government decisions. Drought indices 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. 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 help to ensure that program payments are targeted effectively to assist those most in need. This research could lead to important potential societal and environmental benefits. These applications relate mostly to the vulnerability and adaptability of communities to water scarcity and climatic change.

Expanded contacts in partner organizations:

Some DRI investigators increased the number of partners involved in their projects during the past year. This includes new contacts at Environment Canada in Toronto and in the regional offices for Elaine Wheaton, Geoff Strong, Ronald Stewart, and Henry Leighton (CRCM modelers). Contacts and partnerships were established with experts in other departments, including Natural Resources Canada (NRCan) and the Canadian Forestry Service (Elaine Wheaton). Elaine Wheaton established contacts with the University of Manitoba and Geoff Strong with experts from the Universities of Calgary and Manitoba. Masaki Hayashi established partnerships with Alberta Agriculture. Contacts were made in the Canadian Wheat Board, Manitoba Water Stewardship, Manitoba Agriculture, Food and Rural Initiatives, and Manitoba's Agricultural Research Development Initiative. A number of these contacts have provided funding and in-kind support 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.

John Pomeroy made contacts with Ducks Unlimited, the Prairie Habitat Joint Venture Policy Committee and the provincial governments of Saskatchewan and Manitoba. Al Pietroniro has developed new partnerships with University of Calgary, increased involvement with RPN in Dorval and now interest from other outside agencies such as Manitoba Hydro.

A visiting scientist took part in some of the research in 2009 and provided a link to the Rubber Research Institute in Kerala, India. The geological weighing lysimeter method is being increasingly recognized for its potential for wide application in testing hydrological models, for real-time assessments and forecasting of droughts and floods, and for tracking of land-atmosphere moisture exchanges in relation to climate and weather prediction models. The compiled observation well records across the prairie region are being shared with provincial groundwater agencies. Discussions about groundwater levels' response to drought and climate variability are ongoing.

Contributions to the reliability of predictive methods:

Developing improved predictive models is a major challenge for DRI. Progress has been achieved in two significant areas, including an improved understanding of critical processes and model development. We incorporated this improved understanding into a numerical framework.

While ocean temperatures provide some of the yearly forcing on the atmosphere, DRI scientists are examining the shorter seasonal or multi-season time scale deep soil moisture anomalies and their influence on atmospheric phenomena. It is hoped that the project of Ken Snelgrove involving the assessment of these influences will lead to the operational assimilation and use of gravity reconstructions of deep moisture within seasonal and longer-term forecast systems.

Hydrological models have been improved as a result of DRI such that they can predict prairie hydrology from small basins. Improvements being made now, CLASS and MEC/MESH code review and improvements, links to NWP through RPN. Validation of hydrology models now includes other parameters including soil moisture, lysimeter data (van der Kamp) and flux estimates. Masaki Hayashi has improved the VSMB model's performance, which in turn improved the prediction of soil moisture conditions associated with drought when the rainfall and temperature fields are known.

Research by Barrie Bonsal and John Gyakum on atmospheric and oceanic variability associated with Canadian prairie droughts has provided a better understanding of the planetary scale circulation patterns accompanying drought events. This work can serve as a benchmark for atmospheric models and their ability to predict the onset and dissipation of these patterns.

DRI work has not yet led to improvements in predictive methods, although some model deficiencies are beginning to be identified. There is some evidence that high-resolution atmospheric models are essential for simulating and predicting drought and its features. Through work on groundwater an improved model for the interactions between the atmosphere and the Assiniboine aquifer have been developed. Some work has been very helpful in identifying the variables that need to be included in prediction systems. Work on aerosols and radiation led to the identification of ways in which the CRCM model could be improved. Moisture demand (potential evapotranspiration) has been shown to be more strongly related to wheat yield and quality than precipitation. In addition, an understanding of boundary layer processes and their effect on the formation of precipitation in the summer was advanced through DRI contributions to the UNSTABLE project. MODIS NDVI (10-day composite) data from late June through late July is significantly correlated to census agricultural region yields of four major crops. Thus, these data can provide a means to delineate the spatial extent of agricultural drought based on yield deviations. Improved accuracy of meteorologically-based agricultural drought indices can therefore be achieved based on these methods.

A group of DRI investigators (Al Woodbury, Masaki Hayashi, John Pomeroy, Al Pietroniro, Ken Snelgrove) are analyzing data and carrying out modeling studies to increase our understanding of the feedback among meteorological forcing, soil moisture, and groundwater. The improved understanding will feed into integrated models of surface water and groundwater, which will be used to examine the response of surface and groundwater resources to meteorological forcing during droughts.

Contributions to funding opportunities and partnerships in other agencies

DRI has facilitated the work of its investigators and partners in other areas, by enabling or facilitating their efforts to acquire support for other related projects. The institutions that participated in DRI generally have much higher visibility, especially on the Canadian prairies. Considerable attention is paid to drought issues in this area of the country. In some cases, DRI projects have led to new initiatives that benefitted investigators, participating organizations, and DRI stakeholders. The monitoring well network has been expanded to the MD of Rocky View and Masaki Hayahsi has secured a new grant ($500,000) from the Royal Bank of Canada to implement the groundwater recharge model coupled with a flow model to seven watersheds within in the MD. The model will be used to support drought-tolerant water resources management for the MD. This is a significant spin-off of the DRI project, which funded the scientific understanding and technology development.

Kenaston field site will be part of a larger AAFC soil moisture mapping experiment to be conducted in the summer of 2010. The experiment will include an aircraft mission and involve NASA investigators as well as Canadian experts.

DRI research is also credited with having helped the UNSTABLE project gain additional support from Environment Canada. The DRI heritage may also lead to funding increases from Manitoba Hydro, but this is far from certain.

Impact of DRI on investigator institutions:

The study has substantially improved graduate student numbers and training at U of S and has strengthened the Centre for Hydrology and its collaboration with NHRC. Graduate students in several university programmes are now experiencing strengthened frameworks for training M.Sc. students in research.

DRI Investigators have broadened the scope and capabilities of their own institutions. DRI research has strengthened Environment Canada and the Saskatchewan Research Council's mandate to consider priority issues, including study of extreme hydrologic events on the hydrology and ecology of Canada. The Saskatchewan Research Council has developed contacts and expanded its use of data sets in conducting drought analysis. In a similar way DRI has benefitted the home institutions of its investigators.

A new partnership has developed with NALCOR Energy (formerly Newfoundland Hydro) which is currently funding two graduate students to assess the impact of climate change on the water resources of Labrador for future hydroelectric development. This project may be extended to address seasonal forecasting including drought prediction.

Links with international initiatives:

DRI has also made substantial contributions to international science activities in the areas of climate and water. The whole DRI effort is closely linked with international GEWEX and WCRP activities on extremes which are being led by Prof. Ron Stewart. DRI is a lead initiative in the GEWEX Extremes activity and also leads in providing input to the GEO work plan in regional drought impacts. In addition to providing leadership on a DRI task related to drought monitoring, work on MESH, NAIS and the Kenaston data are being highlighted as potential contributions to GEO initiatives. DRI also links well with the Institutional Adaptation to Climate Change project (funded by SSHRC), which compares the vulnerability and adaptability of rural communities in Canada and Chile in terms of water scarcity and climate change. Through the efforts of John Pomeroy, DRI also plays a significant role in PUBS (Project for Ungauged Basins).

Anticipated benefits for Canadians.

Although the current benefits of DRI are targeted to its partners and stakeholders, in time it will benefit all Canadians. Anomalies related to the hydrological cycle are an enormous problem. By addressing these issues, DRI and its individual researchers will eventually be able to better cope with such features and provide improved farm and community scale water supply estimation. The largest long-term benefit of DRI for Canadians involves the training of highly skilled workers who will be able to address issues of drought and climate change in the future. DRI trained two M.Sc. students, Heather Greene and Trudy McCormack, who are now both employed by Environment Canada. It introduced these two students to the broader research community, which will undoubtedly benefit them in the future. It also gave these students an opportunity to present their results at national conferences.

DRI research has contributed to the overall goal of developing a better understanding of drought, which benefits Canadians. DRI research provides a solid basis for identifying early signs of drought. They also help us to improve water management and reduce community vulnerability. Improved agricultural drought monitoring and assessment helps all Canadians by ensuring better allocation of public funds in situations where severe drought results in government support.

DRI has helped develop new technologies. A collaborative initiative between McGill University and the University of Calgary assesses the feasibility of using GPS data to enhance our understanding of sub-synoptic evapotranspiration processes in drought-prone regions.

DRI research has contributed to model development, which could improve the forecast system for all Canadians. It is important to note, however, that these improvements will only lead to improved regional forecasts once they are incorporated into the CCRM.

Soil moisture modelling involved significant collaboration and networking with researchers. DRI soil moisture analysis and groundwater work could lead to improvements in the treatment of land surface processes in seasonal forecast models. A link to our 60-year (1950-2009) daily soil moisture data set is available on the DRI website and further collaboration with DRI researchers may take place. Finally, Lei Wen has worked with DRI data manager Phillip Harder to successfully transfer our VIC reconstructed 60-year soil moisture simulation as a DRI data legacy.

Work by Al Pietroniro has improved understanding of water availability for the agricultural industry, provided a better understanding of cold regions hydrology and supporting the needs of Manitoba Hydro and Manitoba Water Stewardship.

5.0 Dissemination of results

|5.1 Publications:

The DRI research results were documented and published in peer-reviewed publications. They were also presented at conferences and documented in conference proceedings and other documentation.

Refereed journal articles:

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Gyakum, J.R.., 2009: Monitoring climate change. *Northwest Territories Research Workshop.*

Gyakum, J.R., 2009: Tropical moisture transport and extreme weather in Canada: Rain, Wind, and Drought. National Center for Atmospheric Research, Boulder, Colorado.

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<u>Related Papers and Contributions</u>

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Beaulieu, C., and E. Wheaton, 2009: Comparing climate trends and extremes: a Saskatoon case study. *Climate Hazards Workshop,* Saskatoon, Saskatchewan, SRC Publication No. 12829-2aD09.

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Wheaton, E., 2009: Climate change: how will it affect Saskatchewan? *Frances Morrison Library*, Saskatoon, Saskatchewan, SRC Publication No. 11178-2D09. 45 pp.

Koshida, G., E. Wheaton, and V. Wittrock, 2009: National Drought Study update: developing the prairies component. *AIRD National Project Review Meeting*, Fredericton, New Brunswick, SRC Publication No. 12803-1D09.

Wheaton, E., V. Wittrock, and G. Koshida, 2009: Confronting climate hazards: implications for vulnerability. *Research for Disaster-reduction from Extremes Workshop*, Winnipeg, Manitoba, (SRC) Publication No. 11178-1D09. 29 pp.

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Wheaton, E., and V. Wittrock, 2009: Climate hazards, impacts and adaptation project: highlights. *Climate Hazards Planning Workshop #2*, Saskatoon, Saskatchewan, SRC Publication No. 12624-4D09. 43 pp.

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Journal articles in preparation:

Bonsal B.E., A. Wheaton Meinert, and E. Siemens, 2010: Characterizing the surface dynamics of the 1999-2005 Canadian prairie drought. *Atmos-Ocean*. Submitted.

Theses and Technical Papers:

Bonsal, B., E. Wheaton, A. Meinert, and E. Siemens, 2010: An assessment of various drought indices associated with the 1999-2005 Canadian prairie drought. *CFCAS Canada, Saskatchewan Research Council.*

Greene, H. Drought and associated cloud fields over the Canadian prairies. Department of Atmospheric and Oceanic Sciences, McGill University, 121 pp.

Trudy McCormack. An evaluation of the Canadian Regional Climate Modelsimulation of the 1999 to 2004 drought over the Canadian Prairies. McGill University M.Sc. thesis, June 2009, 117 pp.

In addition all DRI Investigators made presentations on their work at the annual DRI workshop.

In the past we have posted papers written by DRI investigators on drought-related topics to the DRI web site. As a result of a complaint from a Journal Editor during the past year against this practice of posting papers we have discontinued this practice and now ask the reader to contact the author directly if they wish to see any of the papers listed in this report.

5.2. Dissemination of Information through the media

A number of DRI Investigators and the network manager were contacted after the statement from the Regina DRI workshop was released in March 2009. They were mostly concerned with the consequences of CFCAS not being renewed and the impacts on drought research. More recently, DRI Investigators have given a number of media interviews: Ron Stewart (television, press and radio); John Pomeroy (press and television); Garth van der Kamp (press); and Geoff Strong (radio). In particular, "Whatcha going do when the well runs dry" was the catchy title for one article that appeared in the Western Producer. In 2010, DRI expects to receive some exposure through Environment Canada press releases for a soil moisture experiment that will use some DRI soil moisture sites.

5.3. Visibility for CFCAS

Without exception, DRI scientists who receive support from CFCAS through DRI acknowledge support from CFCAS in a variety of ways including showing the CFCAS logo on conference presentations, and including a sentence recognizing CFAS contributions in journal articles and publications.

6. Data Issues:

6.1. DRI Data Legacy

DRI supports two data managers. One full-time data manager is based in Winnipeg, MB, where data legacy issues constitute the main focus of DRI activities. A second part-time data manger, based in Montreal, QC, looks after DRI data services provided through the DAI system. DRI Investigators have relied more extensively on the DRI data managers as the synthesis activities and the data legacy issues increase in importance. Phillip Harder led in the preparation of a Data Legacy Policy paper which has been reviewed and accepted by the DRI Science Committee. The data legacy envisions that all metadata, as well as those data submitted by individual PIs, will be stored centrally. Table 2 outlines the status of these data sets. It is based primarily on the data submitted by investigators.

6.2. Dissemintaion of DRI data

A number of scientists (Paul Bullock, Masaki Hayashi, Henry Leighton, Al Pietroniro, Ron Stewart) have submitted metadata to the DRI Data Manager for the DRI data legacy. A few (Barrie Bonsal, Paul Bullock, Garth van der Kamp, Charles Lin, Al Pietroniro, Ron Stewart, and Elaine Wheaton) have provided data sets. Some scientists have provided links to their data sets; they will be used by the DRI Data Manager to provide data sets through the DRI Data website as the DRI project comes to a close.

Table 2. Status of Data and Metadata submissions to the DRI Data Manager. Entries with "DM ….." indicate an update or comment provided by the Data Manager.

Investigator	Data Types	Metadata Submission	Central data storage
Barrie Bonsal	Environment Canada data	Meta data being developed but not received by the DM	Data held centrally DM: Some data have been received
Paul Bullock	Crop Yield Data SPI NDVI PAM2nd output	Partial metadata submission, ongoing	Partial data submission, ongoing
John Gyakum	NCEP NARR data	Metadata available	Data held centrally in the DAI system
John Hanesiak	PAM2 outputs	None received	None received
Masaki Hayahsi	Nose Creek Field Data	Metadata submitted	Data held by the investigator
Henry Leighton	Satellite data	Meta data submitted	Data held centrally
Charles Lin	Model output and reanalysis data Modelled soil moisture data	Meta data submitted but not received	Data available through DAIS VIC soil moisture outputs archived
Alain Pietroniro	Soil moisture data	Metadata submitted	Data maintained at the HAL lab
John Pomeroy	CRHM Evap Snow	Partial metadata received	Data submitted to the DRI data manager DM: Data not received
Ken Snelgrove	GRACE data	None received	None received
Ronald Stewart	Radar data	Meta data submitted	Data submitted to the DRI data manager
Geoff Strong	UNSTABLE transect data	Incomplete	Data held by investigator
Garth van der Kamp	Groundwater data Wetland data	None received	Groundwater data received
Elaine Wheaton	Drought Indices	Meta Data Submitted DM: Metadata not submitted	Data have been submitted
Al Woodbury	VIC model output	None received	None received

Table 3. Data and Model data output used in DRI research (by investigator).

Variable	BB	PB	JG	JH	MH	HL	CL	AP	JP	KS	RRS	GGS	GvK	EW	AW
Monthly precip.	X														
Anusplin precip.														X	
CANGRID data			u	X		X									
Weekly stn precip		X					X								
Radar data											X				
Monthly/daily temp.	X	X													
Humidity	X		X												
ISCCP/SRB data						X									
Geopotential height	X		X												
SST values	X														
Sensible Heat Flux					X										
Evapotranspiration		X			X										
Lightning data				X											
PASPC data				X											
Soil moisture					X		X	X							
Borehole temp.															X
River discharge					X		X						X		X
Surface Water Store										X			X		
Snow Water Eq									X						
Groundwater level					X					X			X		X
GRACE data										X					
NDVI data		X		X											
Crop yield data		X		X											
Modelled crop yield		X		X											
CRCM output						X									
GEM model output							X	X							
NARR analysis			X					X							

Some scientists (John Gyakum, John Hanesiak) are making their data sets available themselves. In one case, consultations are being held with Environment Canada about the release of the data to DRI. In another case, no effort has been made in submitting the data to the DRI website. The status of these submissions is outlined in Table 2. Al Woodbury is exploring the possibility of making data available from the northern climate borehole surveys as well as materials from Okanagan project.

7.0 Training

Students and Postdoctoral Fellows

During the past year DRI continued to rely on graduate students and postdoctoral Fellows to undertake much of the research under the supervision of the DRI investigators. Students at both the Masters and Doctoral levels are able to use the results of this research to meet the thesis requirements for their degrees.

Table 4. Graduate Students and Postdoctoral Fellows working in DRI during the past year:

Investigator	Graduate Student	Research Associate
Barrie Bonsal	None	None
Paul Bullock	None	Manasah Mkhabela
John Gyakum	Lisa Hryciw	Eyad Atallah
John Hanesiak	Julian Brimelow	
Masaki Hayashi	Chris Farrow (MSc) Paul Wozniak (MSc)	Getachew Mohammed
Henry Leighton	Trudy McCormack	
Charles Lin	None	Lei Wen
Al Pietroniro	Dean Shaw Habib Mazaheri	Saul Marin Muluneh Admass Mekonnen
John Pomeroy	Robert Armstrong	Kevin Shook
Ken Snelgrove	Sitotaw Yirdaw Clement Agboma	
Ron Stewart	Trudy McCormack (MSc)	William Henson Hannah Carmichael

Geoff Strong	Julian Brimelow * Danny Brown	
Garth van der Kamp	MSc student	PDF (part-time)
Elaine Wheaton	None	Two research associates
Al Woodbury	Smrita Joshi Kibreab Assefa	Lei Wen Youssef Loukili

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
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
MD	Municipal District
MODIS	Moderate Resolution Imaging Spectroradiometer
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	National 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 (Has recently adopted a new name)
PNA	Pacific North American
REDE	Research for Disaster-reduction from Extremes
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
WN2N	Western Canadian Cryospheric Network