

The 2008 Progress Report for the Drought Research Initiative (DRI)



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**2008 Progress Report for DRI
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2008 DRI Progress Report
Project Title: Drought Research Initiative
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1.0: PROGRESS (January 1, 2008 to December 31, 2008)

1.1: Overview of 2008 by DRI Management (Ronald Stewart, John Pomeroy, Rick Lawford)

The period of January to December 2008 has been an exciting time for the Drought Research Initiative (DRI) Network. New scientific discoveries, increasing recognition for the project and new initiatives have all contributed to the enthusiasm. The Network successfully competed for a Supplementary Grant from CFCAS and initiated new activities in information management and evaluation of drought early warning information products by user groups. A new CFCAS project led by Dr. Aaron Berg on seasonal prediction of drought is strongly linked to DRI soil moisture activities and is enhancing contributions to its prediction activities. Highlights of the 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 Drought Characterization Study (Theme 1) has made impressive strides forward during 2008. Investigators also have made notable research advances in Theme areas 2 and 3. However, in spite of this momentum, DRI will be coming to an end in the spring of 2010. Consequently, in addition to documenting DRI's progress in 2008, this report also describes DRI's plans for its phase out and the development of its legacy.

Research Highlights and Theme Assessments:

From a programmatic perspective, it was expected that Themes 1, 2 and 3 would all progress rapidly towards the final objectives during 2008. Theme 1 was expected to take actions to address the gaps in its characterization of the 1999–2005 drought. Theme 2 had identified areas where models need to be improved and was expected to make some contributions by providing the physical understanding needed to improve models, Theme 3 was expected to take advantage of the model data sets that had been assembled, to assess the skills in prediction capabilities and to take steps to improve those prediction capabilities. Integration was also expected to be a central focus for Year 4 of the project. This report documents the ways in which these expectations were met.

Theme 1 continues to advance on two tracks: the first track on drought characterization led by Dr. John Hanesiak of the University of Manitoba, who also has responsibility for the overall theme, and the second track led by Drs. Kit Szeto of Environment Canada (a DRI collaborator) and Ron Stewart of McGill University. As outlined in the theme summary the drought characterization work has made great strides during the past year. The focal point for this effort was a workshop on drought characterization held at the University of Manitoba in September 2008. That workshop reviewed the work that had been done to date on characterizing drought, identified other data sets that could contribute to this effort and gaps that needed more data analysis, and evaluated the products best suited for inclusion in the drought characterization report. As a result of the discussions at this workshop, several publications are under development, including an overall synthesis that will provide an integrated description of how every part of the water and energy balance responded to the environmental (atmospheric, oceanic and terrestrial) conditions that set up the drought anomaly.

The drought characterization activity builds upon the analysis of data sets and model outputs characterizing the various aspects of the drought and its impacts on the hydrosphere. Table 1 provides a summary of the status of work completed to date. During 2008, basin wide cloud and surface hydrology assessments received more attention although more work needs to be done. In some cases there are a number of sources for the data (for example precipitation data) and not all of the data sets are fully consistent. As a result, considerable effort has been directed at evaluating the different data and

reanalysis products. There are also a number of indices used to represent surface dryness and again not all of these indices give a consistent representation of the drought conditions because they give emphasis to different aspects of the drought (e.g., growing season rainfall, etc). An understanding of the strengths and weaknesses of these various indices and data products would enable DRI to inform the North American Drought Monitor and other users about better ways to monitor drought as a result of this effort.

Table 1. Summary of analyses carried out in Theme 1 drought characterization activities.

Variable	Prairie-wide
Drought indices	**
Teleconnections	**
Precipitation	**
Clouds	*
Soil Moisture	**
Streamflow	*
Groundwater	*
Surface Hydrology	**
Water and Energy Budgets	**

* — data sets assembled
 ** — data sets assembled and analysis completed

Work on the second Theme 1 track is also progressing. Analyses of the water budgets have been carried out and it is possible to see the migration of the drought over the region throughout its duration. The anomalies introduced by heavy rains in southern Saskatchewan in June 2002 are very dramatic when viewed in the context of the regional water and energy budgets under drought conditions. Another unique feature is the very wet period that brought the drought to an end (at least from a meteorological perspective) in Manitoba and in parts of Saskatchewan and Alberta in the spring of 2005.

Theme 2, which emphasizes process understanding, is advanced through data analysis, targeted field campaigns and experiments, and process model studies. During 2008, Theme 2 has progressed under the leadership of Dr. Masaki Hayashi from the University of Calgary and Dr. Barrie Bonsal of the University of Saskatchewan who provided support on the atmospheric side. A major challenge of this theme is to integrate process understanding across scales and across media (land and atmosphere). As DRI moves toward formalizing its legacy, there will be a need to consider all of these processes and their supporting data sets and model outputs in a more integrated way. Several themes are emerging as focal points for this integration including precipitation, evapotranspiration, soil moisture, snow processes and groundwater.

Several projects that study the large scale processes and patterns that lead to precipitation deficits on the Canadian prairies are demonstrating that teleconnection patterns are not enough to understand how precipitation will respond to 50 KPa patterns – we must also understand how these patterns control the synoptic processes that are responsible for the formation of precipitation. This work has examined the influences of different flow regimes associated with the larger teleconnection patterns on the placement of the jet stream and the upper ridge over western Canada during positive Pacific North American (PNA) oscillation conditions. During the past year, studies have shown how these large-scale processes interact with synoptic conditions to control cloud distributions and influence the horizontal and vertical distribution of moisture in the atmosphere. Additional surface forcing by different land cover types in the foothills of the mountains lead to the development of additional instability and contribute to the redistribution of moisture through convective overturning and especially during thunderstorms.

This theme includes evapotranspiration studies and the role of surface hydrology, soil moisture budgeting and plant phenology in controlling evapotranspiration.. In some areas, such as the Assiniboine Delta Aquifer (ADA) where the soils are very sandy, the influence of groundwater on evapotranspiration is also

being measured and modelled. In addition the vegetation in this area is effective in the recycling of moisture. Some of this work involves the further exploration of ideas that were first discussed at the DRI Evaporation Workshop in Saskatoon in May 2007. Results from these studies will be published in a special issue of the Canadian Water Resources Journal in 2009.

Theme 3, which is led by Dr. Charles Lin of McGill University, also made significant progress in 2008. This progress is evident in three areas: (i) precipitation and other atmospheric parameters, (ii) soil moisture and runoff generation, and (iii) groundwater. The work in Theme 3 includes the analysis of model outputs to assess how well current models predict drought and what steps should be taken in order to improve their ability to predict. It also assesses the extent to which models can simulate drought and various impacts of a drought event, and the benefits of improving parameterizations that have been calibrated or designed for drought conditions. Advances were made in evaluating and improving both atmospheric and hydrological prediction systems through the examination of model simulations and modeling studies.

Predicting precipitation is arguably the most important and most difficult component of drought prediction. It represents the major prediction challenge because of the wide range of space and time scales of precipitation phenomena and the diversity of processes that give rise to occurrence. Within Theme 3 evaluations of the adequacy of historical seasonal forecasts have been carried out. While seasonal forecasts for geopotential heights and temperature show some skill there is no skill in seasonal precipitation forecasts at present. The role of different data sets used in forcing these models has been evaluated. Furthermore, an evaluation of the ability of models to simulate the drought have been undertaken and have shown that some models have more skill than others for some aspects of a drought event.

Work on the improvement of models has come mainly through the improved parameterizations for hydrological models. For the first time, the Cold Regions Hydrologic Model (CRHM) has assembled blowing snow redistribution, snowmelt, infiltration into frozen soils, evapotranspiration, depressional water storage and runoff mechanisms with success in modelling well drained and poorly drained prairie basins in drought. Soil moisture is being examined using the Variable Infiltration Capacity (VIC) model and new methods of representing the non-contributing areas of the Canadian prairies are underway. Soil moisture will continue to be a critical aspect of this theme, thanks to strong collaborations between DRI and a new project on soil moisture assimilation in Numerical 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 result in landscapes that are not conducive to producing surface runoff (areas such as the ADA). This work is focusing on the development and calibration of a new version of the Canadian Land Surface Scheme (CLASS) model (gCLASS), which will have a groundwater component and, when coupled with an atmospheric model, will provide a full suite of atmospheric and hydrological variables.

DRI is moving toward the development of its legacy. Since one of the primary objectives of DRI was to improve the capabilities to predict drought then, at a minimum, DRI needs to identify its contributions to drought prediction and demonstrate how it has improved the prediction drought. 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 what gaps remain that must be addressed by future research projects in order to fully realize improved drought prediction.

Although there is no CFCAS funding for Themes 4 and 5, DRI is 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 evolved in comparison to other “hydroelectric” droughts. DRI has been strengthening its collaborations with Prairie Farm Rehabilitation Administration (PFRA) by its discussion of drought policy issues and with provincial agencies through the Drought Early Warning System (DEWS) and some specific model development activities to improve provincial drought information services,

Secretariat Update:

The Secretariat organizes and summarizes actions from monthly teleconference calls of the DRI Science Committee (SC), as well as Board of Directors (BOD) and Partner Advisory Committee (PAC) teleconference calls. The Secretariat supported BoD and PAC meetings, helped to organize science workshops including the Annual DRI Workshop, promoted DRI through talks and participation in external workshops and working groups (e.g., Canadian GEO activities), interacted with Partners and Stakeholders, and developed and maintained the DRI web site. The staff in the Secretariat were relatively stable during the past year. Rachael Reynen continued as the Financial administrator and Rick Lawford continued as the half-time DRI Network Manager. Patrice Constanza continued as a McGill data manager.

A highlight of 2008 was the development and implementation of a successful proposal to CFCAS for supplementary funding. This funding has enabled DRI to hire a full time data manager and to fill the gap created in 2007 by the departure of Matt Regier who was funded by Environment Canada. After an extensive search for a suitable candidate, Phillip Harder was hired in September 2008 to serve as the western data manager. Since joining DRI he has been actively collaborating with Drought Early Warning System (DEWS) to develop the necessary data inputs, developing standards for metadata, reviewing DRI data holdings and planning to develop the legacy DRI integrated data system.

Visibility:

The annual DRI workshop held in Calgary in January 2008 was a highlight with more than 70 people including a number from the Alberta government in attendance. There were several radio and TV interviews with the French stations giving particularly good coverage. Following the workshop, an interview on DRI and drought was conducted by CTV on Canada AM. The DRI web site, monthly teleconference calls and periodic topical workshops continue to facilitate DRI communications both internally and externally. Peter Lawford a student at the University of Manitoba continued to serve as the DRI Webmaster during 2008. Two new features were added to the DRI web site during the past year - the Canadian GEO Soil moisture activities and the GEWEX Extremes web site. 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 PIs or the Network manager at CMOS, CGU, AGU, the IP3 and WC2N Science meetings, and the North American Drought Monitoring meeting.

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. The second project included in the DRI proposal to CFCAS was the Drought Early Warning System (DEWS) that resulted from the work of the PAC. This project is being led by Nancy Lee and Harvey Hill of PFRA in conjunction with their Drought Preparedness Project (DPP). In this activity they ask users to provide information on how they would adjust their activities if they had access to certain types of information (e.g., accurate seasonal forecasts). The DEWS component focuses on new types of information that DRI is prototyping for use in understanding and monitoring droughts.

Workshops:

In addition, to its annual workshop, DRI holds topic-specific workshops. The Drought Characterization workshop was hosted by John Hanesiak at the University of Manitoba in Winnipeg in September. This workshop which attracted more than 30 specialists provided a review of the work DRI had already done on drought characterization and an assessment of the work that remained. As follow-up from this workshop, an extensive resource document and several journal papers will be developed on different aspects of the 1999–2005 drought. In 2009, DRI is planning to have topic-specific workshops on precipitation and drought indices, surface hydrology, and possibly prediction.

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 while the progress in Theme 3 has incorporated more of the hydrological prediction activities than envisioned in the original milestones. Theme 1 will continue to need to be funded at current levels because a substantial effort will

be required to prepare and finalize the descriptions of drought. Much work remains to be done on Theme 3 and on Themes 4 and 5 which have not been supported for focused study. In addition, work will progress over the next year on an overall synthesis article of drought and DRI. DRI also needs to finalize its decision to move ahead on a Phase 2 proposal and work actively towards this goal.

1.2: Theme Summaries

1.2.1: Theme 1 Summary (Summary by John Hanesiak):

The primary Theme 1 objective is to quantify the physical features of the 1999–2004/05 drought and to 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, however, this was unavoidable in light of the overall scope of the paper. We are now planning a Fall 2009 submission in which many of the products and analyses highlighted here will be integrated more fully. Various researchers in DRI (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.

The larger scale atmospheric circulation patterns have been analyzed using a variety of gridded reanalyses data such as NCEP and ERA40, focusing on monthly and seasonal circulation anomalies. Last year, it was reported that the primary characteristics of storm tracks were frequently located either to the north or south of the Prairies with a series of differing patterns which each had the impact of limiting moisture transport into the region (Gyakum, Bonsal). A new finding shows 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 results in anomalous dry spells. Other major circulation pattern regimes conducive to the drought are currently being investigated with respect to sub-synoptic scale forcings and potential vorticity (vertical motion). This will elucidate sub-synoptic versus synoptic scale interactions and forcing mechanisms. New analysis is also ongoing focusing on linkages between many drought indices and major teleconnections that affect the Prairies (Bonsal and Shabbar). Preliminary results indicate several significant relationships between the drought indices and individual teleconnections such as the PDO and PNA.

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 with ANUSPLIN possessing more spatial detail due to its higher resolution. Monthly maps of CANGRID and ANUSPLIN 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 with the worst being in Alberta and less so toward Manitoba, however, the variability of this was marked depending on the year and month. For example, NE Alberta experienced the largest number of months with drought while southeast Manitoba experienced the fewest months with drought.

Mappings of several drought indices (monthly PDSI and SPI and others) have been generated (Bonsal, Hanesiak, Wheaton) and are being used in teleconnection studies mentioned above (Bonsal). These maps are also being used in the Theme 1 journal article to spatially/temporally characterize the drought. Large-scale soil moisture conditions have been evaluated during the drought based on 0.5° resolution water balance model (c/o Climate Prediction Center of 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 U.S. During 2002, the soil moisture deficit worsened and spread eastward to cover the entire southern Prairie Provinces.

Regeneration of prairie wide daily crop root-zone soil moisture (RZSM) and evapotranspiration (ET) patterns using the PAM-II crop model are being produced based upon new research that has improved the PAM-II simulations (see Theme 3 discussion) (Hanesiak). Work is also continuing to associate lightning with spatial ET and RZSM (Hanesiak, Stewart). Preliminary analysis suggests a statistically significant relation between very low ET / RZSM and abnormally low lightning events during the drought in some cases. This suggests 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). This may have significance for wet/dry boundaries in the boundary layer that can influence summer convective processes.

A comprehensive baseline climatology of water and energy budgets for the Saskatchewan River Basin, including water and energy budgets for part of the 1999-04 drought period, was developed from different datasets and results are published (Stewart, Szeto). Quantification and analysis of spatial and temporal variability of water and energy budgets have been completed for the Prairie region including budget anomalies during major drought episodes within the 1960–2005 period 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 which resulted in reduced winter precipitation and spring snowcover. The reduced snowcover in spring contributed to the soil moisture deficits in the region during those two years which in turn were linked to the 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 show 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 2001/02, possibly signifying a lag effect from snow cover on soil moisture reserves over the region. The snow depth analysis and microwave SWE data reveal generally negative anomalies over the southern prairies during the 1999/2000 to 2004/05 seasons that 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 climatology during drought. It was found that the regions that had the most months with “dry” and “extremely dry” SPIs (Standard Precipitation Index) 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 (Sept. – Feb.) had more dry months than the spring and summer seasons. There is a small but clear signal in the relationship between cloud amount anomaly and SPI, with increasingly more positive SPI (wetter than normal conditions) being associated with positive cloud anomalies and increasingly more negative values of SPI (drier 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. When stratified by cloud type, interestingly, the correlation between cloud amount anomaly and SPI was greatest for high cloud.

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 short-duration deep convection. Other wet events are believed to be the result of more stratiform precipitation and longer duration events. Analysis of these events is ongoing.

Monthly and annual CMI maps over the entire drought period have been produced showing the relevant aspen growth and die-back features over the boreal zone (Hogg). Forests respond more slowly to drought than grasslands and agricultural zones, hence, monthly time scales or longer are more appropriate for examining 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 less than 170 mm (58% below normal), and CMI values indicated conditions that were the driest ever recorded in over 100 years. Biophysical monitoring at the 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 CCRS of NDVI and NDVI anomalies have also been recently produced (Yang, Wang, Trichtchenko). Intercomparison of all of 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 also begun on compiling the final years of agricultural drought index and wheat yield data (Bullock). The goal is 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.

A detailed description of the drought from the St Denis National Wildlife Area, SK is underway (Pomeroy). Reliable datasets of incoming solar radiation, temperature, humidity, wind speed, precipitation, soil moisture, snowpack 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 CRHM platform to characterize the drought over larger spatial scales is ongoing. It was found that NCEP precipitation products are not sufficiently reliable for hydrological analyses on the Prairies. CRHM stream and wetland basin models have also been developed, and have 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, however, 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 basin models will be used over a prairie wide basis in future work, driven by a combination of gridded station and reanalysis data.

Some ground water observations and trends have also been found. A survey of the Alberta Environment Groundwater Observation Well Network (GOWN) indicated that the groundwater level was steadily going down in some regions, and was found to be due to over pumping, a conclusion that was proven in the past year. The effects were particularly pronounced during the drought. This points out a need to use an integrated approach, rather than the 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 among groundwater level, water usage, and meteorological forcing in southern Alberta is still progressing. Similar ground water observations have been obtained in the last year for the Assiniboine Delta Aquifer (ADA) in Manitoba and work is ongoing to reveal any trends during the 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 shows that shallow wells were noticeable depleted during the drought and recovered shortly after, whereas, the deeper wells act 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 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 4X daily global analysis from the Canadian GEM. Both model and observation of moisture during the drought period is represented by a reduction in moisture of approximate 60 mm water equivalent during the fall of 2003 averaged over the entire SRB. Beyond 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 wide spread 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 correlated during a majority of the record. Not all wells show this behaviour indicating the local influences on the regional water balance are

not all captured by GRACE. GRACE downscaling results to well observations correlated to a high of $R=0.8$ to a low of $R=0.5$.

1.2.2. Theme 2 Summary (By Masaki Hayashi):

Objective

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

Milestones for Year 1–3

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

Progress Summary

The following summary is organized according to the spatial scale from continental-scale atmospheric processes to plot-scale hydrological processes. To discover the atmospheric circulation regimes that are particularly pertinent to droughts in North America, we have conducted theoretical studies of blocking using the National Centers for Environmental Prediction (NCEP) 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 Pacific North American (PNA) pattern index, as the positive PNA phase is associated with anomalous mid and upper-tropospheric ridging in western Canada. Gyakum's study has identified a significant trend in the PNA index towards positive values of the past 50 years. However, the precipitation deficits at several locations are not correlated with any of the established teleconnection indices such as the PNA and the El Niño Southern Oscillation (ENSO). Therefore, we are analyzing the different flow regimes that contributed to the length and severity of the recent Prairies drought: (1) northward-shifted jet stream and storm track, (2) western British Columbia meridionally-oriented ridge/trough couplet, and (3) the positive phase of the PNA.

CanGrid precipitation data are being used to examine the spatial distribution of the severity of drought. Leighton also examined the relationships between cloud properties and precipitation using the International Satellite Cloud Climatology Project (ISCCP) Surface Radiation Budget (SRB) data set. When cloud amounts were averaged for each month and over all $1^\circ \times 1^\circ$ grid squares, there was a small but clear trend for drier months to have less cloud cover. However, there was considerable spatial variability. For the recent drought (1999–2004), the greatest negative cloud anomalies in dry months were in central Alberta and the southern portions of all three Prairie Provinces.

On a smaller scale, Stewart is carefully examining the June 2002 major storm event to understand water vapour flux around and within the storm system during the drought. A detailed analysis was also conducted of the possible occurrence of virga using the sounding data near Edmonton over the summer months of 1999–2005. The results imply that 10–25% of the soundings were conducive to virga – precipitation may be forming aloft but it would not reach the surface.

Convective processes related to storms were investigated over the Alberta foothills during UNSTABLE 2008 experiment using mobile transects across “drylines” (i.e. summer Chinook effect). From these data, it is believed that the large scale moist/dry gradients associated with large regions are significant for drought processes. Drought may be initiated as moisture cycling (and storms) is terminated over a region due to lowering soil moisture, while the cessation of drought may be signalled by an outbreak series of thunder storm events associated with the moisture cycling (Strong). We have also identified the key convective and non-convective forcing mechanisms during the drought (2000–2004), and

quantified the ability of using soil moisture as a seasonal predictor of summer severe weather on the Canadian Prairies.

Several studies have been conducted to understand, quantify, and model evaporation, as it provides a coupling of atmospheric and terrestrial energy and water cycles. We examined the point-scale field data collected by eddy covariance systems at Fluxnet sites in Alberta and Saskatchewan, and the West Nose Creek watershed near Calgary. The detailed analysis showed that plant roots utilize deeper sources of moisture during droughts and the grasslands are more sensitive to moisture deficit compared to forests. A new method was developed to estimate spatially distributed evaporation on heterogeneous landscape from point-scale data, using an index-based remote sensing approach. Deep geological weighing lysimeter wells are used to improve the characterization of soil moisture budget, particularly with regards to estimating evaporation during the drought when soil moisture stress is extreme and deep-rooted vegetation tends to draw on deeper groundwater stores. Using the field data, the performance of Prairie Agro-Meteorological Model (PAM2) was tested, which showed that PAM2 is skilful at modeling the day-to-day and year-to-year variability in evaporation, and is capable of capturing the differences between barley and short-grass prairie. Some of these results have been submitted to the DRI evaporation special issue of Canadian Water Resources Journal.

Overall, significant progress was made in understanding the atmospheric and hydrological processes and feedbacks at various scales, models were selected and tested, and new hypotheses were generated. Some results have already been published or submitted to journals. Therefore, all milestones for Theme 2 have been achieved.

Outlook for 2009:

During the coming year, data analysis and modelling will be continued to understand the atmospheric and hydrologic processes. Focussed efforts will be made in the following areas. We will examine the relationship between the drought and various indices and their combinations, which will include the PNA, southern oscillation index (SOI), Pacific decadal oscillation (PDO), and several others using multivariate analysis. We will examine the synoptic-scale vertical motions and moisture budget associated with the generation, maintenance, and the decay of the relevant circulation regimes. We will examine the moisture transport, particularly the “Pineapple Express”, focusing on the details of how strong latent heat release affects diabatic ridging and the displacement of the mean jet to the north of the drought region. We will assess the reliability of ICSSP products by comparing them with the cloud data derived from Moderate-resolution Imaging Spectroradiometer (MODIS) satellite images, and will look for evidence of a connection between increased aerosol optical depths and reduced precipitation. We will continue to evaluate the land-surface models including PAM2, Cold Region Hydrology Model (CRHM), Versatile Soil Moisture Budget (VSMB) and a few others. We will use the new index-based remote sensing approach to examine variation in evaporation over the entire Canadian Prairie region during the drought period. We will couple the land-surface models with groundwater flow model to examine the effects of drought on groundwater resources. These models will be used to evaluate the spatial variability of drought conditions over the Canadian Prairies, and also will be forced by Canadian Regional Climate Model (CRCM) to assess the effects of projected climate change.

1.2.3. Theme 3 Summary (by Charles Lin):

Theme 3 has made significant progress towards its goal of assessing and reducing uncertainties in the prediction of drought and its structure. This section summarizes the progress made in three areas: (i) precipitation and other atmospheric parameters, (ii) soil moisture and runoff generation, and (iii) groundwater. We conclude with an outlook for 2009.

(i) Precipitation and Other Atmospheric Parameters

- Hanesiak has continued the evaluation of precipitation and temperature simulated by two versions of CRCM, the first coupled to the force restore land surface scheme and the second to CLASS. The CLASS version generally produces better results.
- Stewart has continued his analysis of operational seasonal predictions of precipitation anomalies during the recent drought. Performance is in general poor, partly as a result of the model missing individual, major precipitation events.

- Leighton evaluated the CRCM simulation of precipitation and cloud amounts for the period 1999–2004 using CANGRID and satellite data respectively. The relationship between cloud anomalies and the SPI index was also examined.
- Pietroniro compared different precipitation products over the South Saskatchewan River Basin (CaPA, GEM and gridded observations from Environment Canada archive). WATFLOOD was also run using the different precipitation products as forcing to examine the sensitivity on the simulated hydrograph.
- Szeto has used different regional climate models (CRCM and other RCMs from US and Germany) and data assimilation systems (NCEP, ERA40, NARR and GEM) to assess the extent to which the 1999–2004 drought was simulated.
- Strong has continued his work on the quantification of micro-scale drylines and mesoscale moisture gradients across varying land covers, such as between wheat crop and prairie grass.
- Lin examined the seasonal forecast by GCM3 (coupled to CLASS) of 500 hPa geopotential height, surface air temperature and precipitation, over the period 1969–2003. There is some skill for the former two parameters, but little skill for the third. The model had difficulty in forecasting drought events on the seasonal time scale during this period.

(ii) Soil Moisture and Runoff Generation

- Hanesiak has collected and examined hydrological and climatological data from the Burntwood River watershed. The data are being used to calibrate and validate the distributed hydrological models WATFLOOD and VIC, with the intention of using the validated models for hydrologic change assessment.
- Pomeroy has used the CRHM in two model configurations, a small well drained watershed with a first order stream, and an internally drained wetland with the adjacent land, to simulate snow accumulation, blowing snow redistribution, snowmelt, infiltration into frozen soils, evapotranspiration, soil moisture balance, runoff, wetland level and first order streamflow for the climate normal period 1961–1990, as well as the drought period 1999–2005.
- Lin has used VIC to reconstruct a data set of 56-year (1950–2005) daily soil moisture values for three soil layers (0-20 cm, 20-100 cm, and 0-100 cm) for the Canadian Prairies (1,964,000 km²), with the results available for DRI researchers on the web at <http://www.meteo.mcgill.ca/~leiwen/vic/prairies/>. Non-contributing areas are treated in runoff generation, resulting in improved hydrograph simulation; this is done in collaboration with Pomeroy. A real time drought monitoring and short term prediction scheme has also been implemented. CLASS will be set up in a stand-alone mode over the Prairies; this is done in collaboration with Aaron Berg of the University of Guelph.

(iii) Groundwater

- Hayashi has made improvements in the evaporation and snowmelt modules of the groundwater recharge model VSMB, using field data collected at the West Nose Creek watershed.
- Woodbury has continued to develop a groundwater model (gCLASS) that couples the flows in the unsaturated and saturated zones based on an improved version of CLASS. With Van der Kamp, he has evaluated the soil moisture and temperature simulated by gCLASS using data from the BOREAS Saskatchewan site has been performed. Preparatory work to run gCLASS in stand-alone mode over the Prairies has started, in collaboration with Snelgrove and Lin.
- Snelgrove is a collaborator in the Woodbury project. He is also working with US colleagues to test a coupled land surface and groundwater scheme (ParFlow). Pietroniro has developed a hydrological modeling tool (MEC, MESH) and is testing it over the South Saskatchewan River Basin focusing on the prediction of soil moisture, runoff, groundwater, evapotranspiration and snow processes.

Outlook for 2009:

A major focal point for 2009 will be the synthesis of results obtained in the past several years of DRI research. The synthesis will address issues such as the predictability of the 1999–2005 drought on different time and space scales; the strengths and weakness of different models, both atmospheric and

hydrological, and the coupling between them; and ways to enhance predictability up to the seasonal time scale.

1.2.4. Theme 4 Summary (Barrie Bonsal)

The Theme 4 objective of DRI is to: *Compare the similarities and differences of the recent 1999-2004 Prairie drought to previous droughts over this region and those in other regions, in the context of climate variability and change.* Within this main objective, the following questions were proposed to be addressed:

1. How do the physical features, processes, and feedbacks of the recent Canadian Prairie drought compare with a) previous Canadian Prairie droughts, b) Canada-wide droughts, c) US Great Plains droughts, and d) droughts across the world?
2. How does the prediction of the recent drought compare with predictions of other droughts?
3. How does the recent drought compare with past climate variability and projected climate change?

The research plan for the analysis of historical droughts included the following impacts:

1a. Physical Features Comparison with Other Prairie Droughts:

Individual studies (from Themes 1 & 2) would compare similarities/differences of various physical features. The extent of these comparisons will depend on specific variables and data availability. The methodology would involve direct comparisons with identified droughts as well as, determination of trends and variability during period of record. In addition, other severe droughts will be identified using various meteorological, agricultural, and hydrological indices.

1b. Physical Features Comparison with Droughts in Other Regions:

This research would focus on larger-scale aspects such as teleconnections, soil moisture anomalies, moisture sources, and drought indices. It would specifically address Canada-wide droughts, US Great Plains droughts, and droughts in other regions of the world through a global focus on the water cycle.

2. Prediction Comparisons:

Several multi-decadal model data sets including the current drought period will be available based upon Theme 3 studies. It is proposed that these data sets will be analyzed to compare the prediction of recent Prairie drought with other identified droughts that contain these modeled data.

3. Comparisons with Past Climate Variability and Projected Future Climate Change:

The identified similarities/differences as well as, analysis of past trends and variability in physical features, will place this recent drought in the context of past climate variability during instrumental and paleo-climatic period of record. By using climate output from GCMs/RCMs, the recent drought will be placed in the context of projected future climate change (e.g., how often can we expect this type of drought in the future?)

Although Theme 4 was unfunded, there has been some progress made by several DRI researchers while contributing to research directed toward Themes 1 to 3. This has mainly involved the characterization of this recent drought in terms of historical variability. Specific contributions related to Theme 4 have included:

- Correlating seasonal teleconnection index values of the SOI, PDO, PNA, AMO, AO, and NAO with drought indices over the Canadian Prairies (SPI, PDSI, PDSI Z-value) at various lag and lead times for the entire instrumental period of record. 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.
- Comparing the 2001/2002 Canadian Prairie drought (in terms of extent and severity) to those that occurred during the instrumental period of record as measured by the PDSI and SPI. There has also been some preliminary analysis toward placing this drought into the context of future droughts using projected temperature and precipitation changes from GCMs.
- Examining the relationship between precipitation and clouds over the Prairies for the 20-year period 1984 to 2004 using data from the ISCCP SRB datasets.

- Studying the details of secular changes in atmospheric circulation regimes, and other atmospheric circulation anomalies, during the past 60 years. This is a first step towards a deeper understanding of the associated drought structures during the 1999-2004 drought as they compare to historical major drought episodes.
- Assessing and comparing water and energy budget anomalies for different drought periods over the Prairies.
- Comparing boundary layer moisture cycling and the diurnal cycle of moisture from varying land cover during the 1999-2004 drought to the drought that occurred in 1988.
- Examining hydro-meteorological extremes from historical time series of temperature and precipitation from +100 year old high quality datasets. 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 period of record. Precipitation data appear to be more stationary, but their multi-fractality shows much greater temporal variability.
- Compiling region-wide observation well data observations over the period 1965-2005 and lake level data from 1910-2007 has helped establish a basis to compare the effects of the recent drought with previous droughts.
- Beginning to address drought in other regions of the world through international GEWEX and in particular, examining whether major precipitation events mark the end of meteorological drought.

1.2.5. Theme 5 Summary (By Elaine Wheaton):

Although some DRI research results contribute more directly to this theme than others, all DRI research contributes to Theme 5, whose aim is “applying progress to address critical issues of importance to society. “ The overall objective of DRI relates directly to this theme’s objective as progress is obtained by better understanding and predicting Canadian Prairie Droughts. Many of the researchers are working with partners and these linkages are benefiting the work of the partners, and thus bringing benefits to society. Examples are the direct inputs from DRI research have been made to an Alberta Agriculture model where soil moisture process understanding has been incorporated to improve model parameterizations, and the advice DRI provides to PFRA discussions on drought monitoring. Other examples of products from this work are already appearing in the literature, including lessons learned from the characteristics, impacts of and adaptations to this recent massive drought, community case studies regarding water scarcity, and of the role of institutions.

The drought work is useful in the design of sustainable resource management strategies and in the development of drought warning strategies. For example, the Cold Regions Hydrological Model (CRHM) research will provide information for sustainable water management of wetland dominated basins during drought and pluvial periods. Another example is the improved understanding of groundwater resource dynamics including natural recharge rates after groundwater pumping which is being used by municipalities to set guidelines for aquifer management.

In the coming year it is anticipated that a users’ workshop will bring DRI researchers and partners together and will significantly expand the use of DRI research results.

1.3: Plans for Research Between January 2009 and June 2010

During the next year DRI will be completing a number of its scientific projects and organizing its findings into synthesis papers and other legacy documents and systems. Two major legacy papers that will be advanced to the publication stage in the coming year are a Drought Synthesis paper being led by Prof. Ron Stewart and a Drought Characterization paper being led by Dr. John Hanesiak. Three legacy activities that are being supported by the supplementary CFCAS grant include the development of an integrated data system containing the data from DRI; the assessment of the benefits of different DRI products for the user community through the Drought Early Warning System (DEWS) activity and the

completion of a layman's publication describing the results of each project and the overall DRI project in the context of Sustainable Development.

An overview of the plans for each theme has been outlined in the theme sections. This section deals with the specific shorter term research goals for DRI Investigators in the coming year. In reviewing these specific tasks it should be remembered that Tasks initially undertaken in support of Theme 2 – Drought Processes have become more relevant and connected to Theme 1 – Drought Characterization, or to Theme 3- Prediction Systems, as DRI has progressed. For more detail on the specifics of these plans the reader is referred to the detailed Investigator reports contained in Appendix A of the complete document.

Short Term Goals for Theme 1 – Drought Characterization:

- The persistence of various atmospheric, oceanic, and land surface variables during the 1999–2005 drought will be assessed (Bonsal).
- Multivariate analyses of atmospheric patterns will be undertaken to determine if combinations of these large-scale teleconnections were responsible for the initiation, persistence, and termination of the 1999–2005 drought (Bonsal).
- An assessment of agricultural drought indices will be completed in early 2009. A subset of the best indices will be used to characterize the 1999–2005 drought and to serve as a basis for future drought studies (Bullock).
- The case study on groundwater level change before, during, and after the 1999–2005 drought will be extended (Hayashi)
- CRHM runs will be completed for grids covering the Prairie region to produce first order basin hydrology and used in the drought characterization (Pomeroy).
- Estimates of the prairie water balance using the GRACE gravity satellite system will continue to be developed and inter-compared with independent observations of land surface moisture (Snelgrove).

Short Term Goals for Theme 2 – Drought Processes:

Hydrologic processes:

- A remote sensing evaporation estimation method will be used to examine variations in actual evaporation over the entire Canadian Prairie region during the drought period (Pomeroy).
- Wet/dry soil moisture and ET areas will be identified using the PAM-II crop model over the Prairie-wide region and linking these areas to convective cloud initiation, lightning and storm development (Hanesiak).
- The VIC model will be modified and tested to see how to represent ineffective flow areas of the Upper Assiniboine Basin in Saskatchewan into to this model (Snelgrove).

Atmospheric Processes:

- The observed relationships between teleconnection indices including the SOI, PDO, PNA, AMO, AO, and NAO and drought indices over the Canadian Prairies will be assessed for the entire instrumental period and analyzed to determine if they were also prevalent during the 1999–2005 Prairie drought (Bonsal).
- Studies of the role of marginal precipitation, the occurrence of major storm systems, and cold season features will be undertaken to more fully understand their role on drought structure and evolution (Stewart). The focal topics for these studies will be the June 2002 storm, other major storm events and the ability of models to simulate observed cloud fields.
- Based on recently developed understanding of vertical motions and moisture budgets, analyses associated with the generation, maintenance, and decay of the relevant circulation regimes associated with the various components of the drought will be completed (Gyakum).
- Analysis of the latent heat release effects on diabatic ridging, and the displacement of the mean jet to the north of the drought region will be carried out (Gyakum).
- The relationship of the secular changes in atmospheric circulation regimes to regional climate change, and the associated phenomena of droughts will be studied (Gyakum).
- GPS-derived precipitable water will be analyzed to provide crucial sub-synoptic-scale information needed to enhance our understanding of the impact of evapotranspiration (ET) on

available atmospheric moisture/stability as numerical predictions of ET in operational models are somewhat problematic (Gyakum).

- Moisture cycling research using more case studies from the current drought period will be undertaken (Strong).

Short Term Goals for Theme 3 – Drought Prediction:

- CRHM prairie hydrology model aspects will be used to advance the development of MESH model for Prairie runs (Pomeroy)
- Further improvements will be made in the VSMB model and it will be coupled with a groundwater flow model (Hayashi).
- Completion of a study of the effects of hydrology on fluxes in a Boreal forest using data from the Jack Pine BOREAS site (Woodbury),
- Completion of simulations of the water table in the ADA region and over the broader prairies using the gCLASS model (Woodbury).
- Historical CRCM simulations over the DRI period will be carried out as well as other drought periods, with a primary focus on precipitation and hydrological modeling over specific basins of interest (Hanesiak).

In addition to these plans, the focus of every project in 2009, the final full year of DRI research, is best stated by one investigator whose goal is “to focus on completing work that is underway and on preparation of papers.”

2.0: IMPACT

2.1: Short- and Medium-term Objectives that have been Achieved

A number of short term and medium term objectives were achieved in 2008. The objective of strengthening the data management component of DRI has been achieved through the funding of a Data Manager position while the interactions with users are being strengthened through DEWS. In addition a number of journal papers have been produced to document and disseminate the results of DRI research.

The following paragraphs focus on the short- and medium- term objectives related to the DRI Themes.

Drought Characterization:

The objectives this work were advanced through the Drought Characterization workshop and the leadership of Dr. John Hanesiak in coordinating a synthesis of data sets for use in Drought Characterization. Specific work achieved within the Themes included a preliminary series of meteorological-based agricultural drought indices (Bullock) that has been tested against an observational data set; this effort is being followed by a full assessment of meteorologically-based agricultural drought indices. Three gridded datasets (ANUSPLIN, CANGRID, and CRU) have been evaluated to see how well they represent observed station values and to determine which is best suited to quantify drought characteristics over the Prairies (Wheaton). The ANUSPLIN dataset was chosen and the gridded data were used to calculate and map monthly drought indices (PDSI and SPI) and to create animations. Graphics/animations of precipitation, temperature, soil moisture and ET conditions have been produced over the drought period using various datasets to characterize the drought (Hanesiak).

Hydrologic Process Studies:

Hydrologic process research has led to a better understanding of internally drained wetland runoff sensitivity to drought (Pomeroy). Prairie wetland dynamics during drought cycling have been characterized. A method to upscale evaporation rates from a point to a small grid cell using remote sensing has been developed and tested. CRHM has been adapted so that it can simulate the drought hydrology of both well drained and internally drained basins and data assembly for gridded CRHM drought runs is well under way. The PAM2nd model for estimating evapotranspiration has been revised and improved (Bullock). Significant progress has been made in understanding the processes governing the exchange of water and energy between the soil and atmosphere, and how they affect groundwater (Hayashi). The new understanding is being incorporated into a groundwater recharge model.

Atmospheric Process Studies:

A research plan for continued analyses and integration of the results for large scale circulation patterns and drought has been formulated. Precipitation studies, which involved characterizing and interpreting some of the key internal features of drought, have established the importance of marginal precipitation, the occurrence of major storm systems, and cold season features (Stewart) during drought events. Analyses have been completed of moisture cycling and drylines for the western part of the DRI study area using surface and sounding climatological data (Strong).

Prediction System Studies:

A multilayer version of gCLASS with user friendly input/output has been developed and implemented (Woodbury). The coupled hydrometeorological SABAE-HW3D model is also running successfully and serving as platform for interdisciplinary studies. Analysis has shown there is little skill in seasonal forecasts of drought by the Canadian operational and research models. Work is continuing on soil moisture analysis using VIC, CLASS and gCLASS, and on investigating how soil moisture initialization might increase seasonal predictability (Lin).

2.2: The Significance / Impact of the Results Achieved To Date and the Contributions of this New Knowledge

The Impact of the Project on Government Policy Development (federal, provincial or municipal):

DRI hydrological research has had important potential connections with groundwater regulation and policies. For example, the Assiniboine Delta Aquifer (ADA) which serves as a source of drinking water for a large area is also extensively developed for agriculture that requires significant nutrient application. Recent research indicates that there is a high degree of risk to water quality from the farming activities involving nutrients. In response to increasing concerns with rising nutrient levels in surface and groundwater, new provincial moratoriums have been placed on the expansion of livestock enterprises and a regulatory framework is being developed for nutrient management. The new model, SABAE-HW (Soil-Atmosphere Boundary, Accurate Evaluations of Heat and Water), developed in DRI, couples a physically-based, one-dimensional nitrogen transport module to the regional (SABAE-HW) model to quantify the nitrogen budgets of the ADA region so advice to farmers on nutrient management can be provided.

Other practical applications of DRI research have been provided for Rural Municipalities in Alberta. For example, the methodology for implementing locally-based groundwater monitoring networks in the West Nose Creek pilot study has been adopted by the Municipality of Rocky View. Other municipalities are interested in developing similar approaches,

DRI has supported Environment Canada research mandate by providing better understanding of extreme events impacting the hydrology and ecology of Canada. Other services arising from DRI research include information products such as the compiled observation well records across the prairie region that are being developed in collaboration with the provincial groundwater agencies, in the context of how they should respond to drought and climate variability. Prairie province water resource departments have also expressed interest in applying the updated version of the CRHM model and groundwater models, which DRI helped to improve for hydrological predictions of prairie streams and rivers.

Provincial policy development relies on knowing the consequences of certain land management practices such as wetland drainage. CRHM is being used to study the effect of wetland drainage on inflows to the Upper Assiniboine watershed that may affect flows from Saskatchewan to Manitoba.

Impacts on highly skilled manpower:

DRI research is attracting students and young researchers to study issues of drought and extreme events. For example, DRI is undertaking some leading edge research in marginal precipitation occurrence and individual storm events in conjunction with major droughts, topics of great interest to the science community because it does not appear that they have been examined before. DRI also provides great opportunities for discovery for young scientists because it is addressing key aspects of a type of hazardous weather and climate that has not been addressed before. As a result of DRI, the federal

departments and provincial governments have had a pool of highly skilled manpower to draw from as they expand their expertise in areas related to the environment and climate change.

Contributions to Expanded Contacts in Partner Organizations and Increased Cross-disciplinary Cooperation:

As noted in Sections 1.5 and 1.6, DRI researchers have developed a number of new contacts. These linkages and collaborations would not have occurred if DRI had not been funded and the activities had not been launched that have led to the development of this network. DRI network interactions have included collaborations between researchers working on impact studies within and outside DRI as well as the sharing of technologies between the research community and operational communities in Alberta Agriculture and Prairie Farm Rehabilitation Administration (PFRA), DRI has contributed to the collaboration between McGill and the University of Calgary on the GEOIDE network project and its ability to document sub-synoptic evapotranspiration processes in drought-prone regions. DRI has increased collaborations with Universities of Calgary, Alberta and Manitoba, and federal government scientists through work on Global Positioning System (GPS) moisture, drylines and UNSTABLE. These links will continue to broaden as more DRI scientists and others become involved in the completion of the Drought Characterization, the DRI synthesis articles, and the other DRI legacy activities.

Direct collaborations have been developed with the UofM which is working on a water and climate change NSERC project with Manitoba Hydro and Ouranos. McGill Prediction studies have significant collaboration and networking with researchers within DRI and external to DRI including Environment Canada staff. Rabah Aider of McGill University has worked with DRI data managers, Phillip Harder and Patrice Constanza, to make available seasonal forecast data for the DEWS (Drought Early Warning System) component of DRI.

The multilayer version of gCLASS with its user friendly input/output has enabled the University of Manitoba to lead intercomparison studies of their field measurements techniques. This opportunity has expanded partners in a cross-disciplinary framework with Engineering and Applied Sciences (MUN), Geology (U of Calgary) and Biosystems Engineering (U of Manitoba). DRI is participating in the advance of a modern hydrological coupling trend that is bringing together more powerful numerical and optimization tools (Woodbury). The SABAE-HW can be used by Canadian students, trainees and engineers inquiring the effect of climate on soil moisture, temperature, freezing and thawing.

DRI Contributions towards more Reliable Predictive Methods:

DRI has undertaken research that supports the improvement of numerical models used in prediction. These contributions include the identification of weaknesses in the models and in improving the parameterizations schemes used in models for various physical processes. Also, the data sets acquired by DRI provide a basis for testing model improvements in areas where models do not conventionally get tested. The numerical codes for CLASS and MEC/MESH are being reviewed and improved to support better NWP predictions

Blowing snow and groundwater processes have been examined in this way. The importance of blowing snow for runoff generation during drought has been assessed and this process has now been incorporated into Environment Canada's MESH model. As predictive models such as CRHM and MESH models have more complete and representative algorithms for the physical processes they are being applied with reduced or no calibration thereby making them better suited for drought applications where as streamflow often becomes negligible.

Hydrologic models often must progress through a process of calibration and benchmarking before they can be used in prediction. The SABAE-HW model is being benchmarked using actual atmospheric and soil data related to Pine Creek North, one of the thirteen sub-basins of the ADA. The model has been shown to have general applicability in field situations and provides an improvement over the original version of CLASS (2.6). Model improvements are also occurring in operational models such as Alberta's VSMB as DRI investigators work with it to improve its performance and its representation of physical processes.

DRI is also providing better data for model evaluation. The geological weighing lysimeter method is showing increasing promise of wide application for 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.

Through University of Manitoba studies DRI will contribute to the development and testing of a detailed Canadian Land Surface Scheme (gCLASS) calculations of evapotranspiration. This is justified since CLASS has been designed to integrate with components of GCMs and is better equipped to deal with increased the variability and shifts in mean conditions that are expected under climate change scenarios. In addition, DRI soil moisture analyses and groundwater work at McGill could lead to improvements in the treatment of land surface processes in seasonal forecast models.

The GEM model simulates the mass changes in the land surface moisture agree quite well with those measured by the GRACE satellite system leading to more confidence in the GEM outputs for integrated forecasting.

The Impact of the Project on Investigator Institutions:

DRI collaborations at specific universities have led to new initiatives which are outside the scientific framework of DRI. For example, a DRI workshop at the University of Manitoba has provided the framework for pan-university contacts and new partnerships. In particular it led to two DRI Investigators and two other experts reconstructing ground surface temperatures (GST) from borehole temperature (BHT) measurements and using these data to infer rates of climate warming in permafrost areas.

Within universities efforts have led to the development of proposals which may lead to funding increases in the future. Some institutes feel that their prestige has been enhanced through the increased visibility that DRI has given to their contributions and capabilities. Some investigators feel that their experience in DRI has helped them gain credibility and made them more competitive for other funding. For example one University of Manitoba hydrologist has received support for a project entitled, "Water Sustainability under Climate Change and Increasing Demand: a One-Water Approach at the Watershed Scale" in part because of his DRI experience. In another case several University of Manitoba and Saskatchewan investigators are in the process of developing a research proposal for consideration by Manitoba Hydro and NSERC focused on drought and Manitoba Hydro water issues. Small universities such as Memorial University has benefited from having two Ph.D. students funded to study in Atlantic Canada.

Links with International Initiatives and their Potential Impact:

The whole DRI effort is linked closely with international GEWEX and WCRP activities on extremes. One of the DRI PIs, Prof. Ronald Stewart, is the leader for the CEOP Extremes activity with GEWEX and DRI is frequently used as an example of the type of study that should be carried out in other regions of the world. Ron Stewart recently convened a GEWEX Extremes workshop in Vancouver which featured several DRI talks. DRI also has considerable potential to link with the International Human Dimensions Program (IHDP) through the Institutional Adaptation to Climate Change project (funded by SSHRC) that compares the vulnerability and adaptability of rural communities regarding water scarcity and climate change. Some of the DRI research was highlighted at GEO meetings and the MESH and Kenaston data are being highlighted as potential contributions to GEO initiatives.

Anticipated Benefits of the Work for Canadians:

The results from DRI will provide better understanding of the most costly natural hazard that Canadians face. The improved capabilities to monitor, predict and adapt to drought situations through the information DRI provides will be invaluable. For example, the potato growing industry is interested in knowing the quantity of groundwater that is available during droughts. However, DRI is only the first step in fully addressing this problem. Anomalies related to the hydrological cycle are an enormous problem. DRI itself and its individual researchers addressing such issues will eventually contribute to being better able to cope with such features. However, the full exploration of the implications of drought and other hydrologic anomalies for water management, and community vulnerability await DRI follow-on studies to be fully

addressed. DRI research will also lead to improved understanding of water availability for the agricultural industry.

Current (or Potential) Commercial or Social Applications

The results from DRI have many socio-economic implications, particularly in the agricultural sector which is so foundational for western Canada. The applications of DRI information also relate strongly to the vulnerability and adaptability of rural communities to water scarcity and climatic change.

3. DISSEMINATION OF RESULTS

In general, the results of DRI research are disseminated through peer reviewed literature, by presentations at scientific conferences and to the general public through newsletters and similar types of public information documents. The following listing details the publications and presentations in 2008.

3.1: Dissemination of the Research Results During 2008 (publications, papers and posters)

Refereed Journal Articles:

Armstrong, J. P., R. L. Pomeroy, and L. W. Martz, 2008. Evaluation of three evaporation estimation methods in a Canadian prairie landscape. *Hydrological Processes*, 22(15), 2801-2815 (refereed).

Bonsal, B. R., 2008. Droughts in Canada: An overview. *CMOS Bulletin* 36(3), 79–86.

Brimelow, J. C., J. M. Hanesiak, and R. L. Raddatz, 2009. Validation of the Canadian prairie agrometeorological model and an examination of its sensitivity to soil hydraulic parameters using ensembles. *Journal of Agricultural and Forest Meteorology* (in review).

Bullock, P. R., G. J. Finlay, and H. D. Sapirstein, 2007. A preliminary assessment of evaporation as an agricultural drought index for spring wheat yield and breadmaking quality in western Canada. *Canadian Water Resources Journal* (submitted).

Diaz, P. S., B. Kulshreshtha, E. Matlock, E. Wheaton, and V. Wittrock, 2008. Rural community and vulnerability to climate change: Case studies of Cabri and Stewart Valley in southwestern Saskatchewan. *Prairie Forum* (submitted).

Fang, X., and J. W. Pomeroy, 2008. Drought impacts on Canadian prairie wetland snow hydrology. *Hydrological Processes*, 22(15), 2858–2873 (refereed).

Hanesiak, J., A. Tat, and R. L. Raddatz, 2008. Initial soil moisture as a predictor of subsequent summer severe weather in the cropped grassland of the Canadian prairie provinces. *Intl J. Climatology*, DOI: 10.1002/joc.1743.

MacDonald, J., and J. W. Pomeroy, 2008. Gauge undercatch of two common snowfall gauges in a prairie environment. *Proceedings of the Eastern Snow Conference*, 64, 119–126. (refereed).

Fang, X., and Pomeroy, J. W. Modelling blowing snow redistribution to prairie wetlands. *Hydrological Processes* (accepted).

King, J. C., J. W. Pomeroy, D. M. Gray, C. Fierz, P. Föhn, R. J. Harding, R. E. Jordan, E. Martin, and C. Plüss, 2008. Snow-atmosphere energy and mass balance. In: *Snow and Climate, Physical Processes, Surface Energy Exchange and Modelling* (Eds. R. Armstrong, E Brun). Cambridge University Press: Cambridge, UK. 70–124 (reviewed).

- Marchildon, G. P., S. Kulshreshtha, E. Wheaton, and D. Sauchyn, 2008. Drought and institutional adaptation in the Great Plains of Alberta and Saskatchewan, 1914–1939. *Natural Hazards*, 45, 391–411. SRC Publication No. 11899-6A07.
- Marin, S., G. van der Kamp, A. Pietroniro, B. Davison and B. Toth, 2009: Use of Observation Well Records for Confined Aquifers to Evaluate Modelling of Areal Evapotranspiration, Submitted – Journal of Hydrology.
- Raddatz, R. L., and J. M. Hanesiak, 2008. Significant summer rainfall in the Canadian prairie provinces: Modes and mechanisms 2000–2004. *Intl J. Climatology*, DOI: 10.1002/joc.1670.
- Roberge, A., J. R. Gyakum, and E. Atallah, 2008. Analysis of intense sub-tropical moisture transports into high latitudes of western North America. *Wea. Forecasting* (submitted).
- Saiyed, I., P. R. Bullock, H. D. Sapirstein, G. J. Finlay, and C. K. Jarvis, 2009: Thermal time models for estimating wheat phenological development and weather-based relationships to wheat quality. *Canadian Journal of Plant Science* (in press).
- Shaw, D., L.W. Martz and Alain Pietroniro, 2009: Topographic Analysis for the Prairie Pothole Region, Dean Shaw,, Accept with revision – Hydrological Processes
- Shaw, D., L.W. Martz, and A. Pietroniro, 2009: The influence of surface water connectivity on runoff in a prairie pothole region, under review – Journal of Hydrology.
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3.2: DRI Data Management and Data Sharing Activities

DRI has taken a number of steps to develop an integrated data base. The DAI has been developed and the data base has been expanded during the past year by Patrice Constanza and his colleagues to give DRI and other researchers access to output files from various models and reanalysis products. DRI has begun to focus on the development of an integrated data system that will be an important part of the DRI legacy. This work is being undertaken by Phillip Harder who is consulting with the National Center for Atmospheric Research (NCAR) about the best way to proceed with this effort. As the framework becomes clarified, it is anticipated that there will be more structure in the data system. However, even before this framework is in place, there is a very substantial amount of work going on related to data management and dissemination and the development of a DRI data archive, following DRI data management principles. Currently the DRI data system includes data held in both centralized and distributed computer systems.

Data Holdings in a Central Server:

- Data from the large scale circulation studies are being maintained by the DRI data managers.
- Primary data sources for synoptic scale studies include the NCEP global and regional reanalyses are freely available to all researchers through the DAI and through NOAA data systems.
- Model and reanalysis data are available for prediction and predictability studies through the DAI.
- Observation well records for Saskatchewan and Alberta have been submitted to the Manitoba DRI data manager, along with metadata and will be made available through the DRI web site.

Data Holdings in Individual Data Systems:

The following data are being maintained in individual computer systems at present. All of these data are being made available to DRI and other users on a request basis. As the integrated DRI data system is implemented, the metadata from these data sets will be stored centrally while the data themselves will likely be held in a distributed network.

Specific data holdings in individual systems include:

- Hydrologic data in the Centre for Hydrology central archives on a terabyte server. They are being made available to other researchers upon request.
- An agrometeorological database with surface meteorological and soil data from the NSERC wheat quality project set up at the University of Manitoba with potential online access to authorized users.
- Field books containing surface weather data, crop data and soil data from the NSERC wheat quality study (5 locations, 2003 through 2006) that are made available to authorized users.
- Radar data used in precipitation studies currently archived on an individual computer at the University of Manitoba and that can be made available to other researchers.
- Field data from West Nose Creek archived at the University of Calgary and made available on request to DRI Investigators at other universities. The data are being quality controlled for wider distribution. They will be made available any time upon request.
- Data related to thunderstorm droughts available on computers at the University of Alberta. The 56-year (1950-2005) daily soil moisture over the Prairies from VIC available from an individual computer that can be accessed through the DRI web site.
- NAESI data maintained in the HAL data archive and made available on request.

3.3: Outreach and Public Information Activities in 2008

A number of DRI Investigators have contributed to DRI outreach activities. In addition to the 3 French interviews and 1 English interview given at the third DRI workshop in Calgary, the press release issued by the University of Calgary just before the workshop received wide attention.

Other outreach activities included:

- Canada AM Interview on Drought (April, 2008) (John Pomeroy)
- Star-Phoenix Op-Ed, June 2008 (water supply for export) (John Pomeroy)
- Radio interviews with Paul Bullock in October centered around the state of knowledge about agricultural drought and its prediction.
- Article in the Saskatoon Sun, (July 20, 2008), on the role of springs in providing water supplies and ecological refuges during droughts.
- outreach workshops to northern communities in association with John Gyakum's IPY research projects.
- Articles on DRI in the Luminus Magazine v32, no.2 p.12-13 and the Benchmarks Magazine, Winter 2007, p.12 (Ken Snelgrove)

In 2008, DRI held a competition for a poster design. A winning poster has been selected but difficulties have been encountered in finding a high resolution photograph.