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# COMMENTARY

*Ronald Stewart, Co-Principal Investigator, DRI Network*

The Drought Research Initiative (DRI) grew out of a call for research network proposals by the Canadian Foundation for Climate and Atmospheric Sciences in 2002. Severe weather was one of the issues being targeted and this included drought. The Prairies were suffering from a devastating drought at this time so it was a unique opportunity to move forward.

We recognized that dealing with drought meant bringing together a diverse group ranging from large-scale atmospheric scientists to sub-surface aquifer researchers and certainly including many groups affected by this devastating phenomenon. We have, for the first time in Canada, accomplished this. To me, seeing the simultaneous examination of drought from myriad and interrelated perspectives has been the most enjoyable aspect of the network.

It has also been a humbling experience for us all. No matter your research specialization or suffered impact, you learn that your perspective is but one of many. Early on some researchers I knew were somewhat dismissive of drought research. "Drought is a whole bunch of nothing and is therefore of little scientific interest" is such a view. You can see by the many sections of this document that this is far from the truth. Although DRI is achieving its objectives, we also realize that it is but a start to adequately addressing and coping with drought, and drought in turn is just one part of the overall issue of extremes and climate.

I would like to thank everyone who contributed to DRI. This includes researchers from many institutions, government representatives from seven jurisdictions, as well as groups and individuals directly impacted. A special thank you is directed at the DRI Secretariat based at McGill University and the University of Manitoba.

DRI is making a difference and its legacy will be felt long into the future. I hope that you enjoy this document that highlights a few of its contributions.

# COMMENTARY

*John Pomeroy, Co-Principal Investigator, DRI Network*

The Prairie drought of 1999-2005 was one of the most expensive natural disasters in Canadian history and a devastating experience for all Prairie residents. Its impact on agriculture, forestry, hydroelectricity, tourism, government, and other sectors was as dramatic and severe as its debilitation of forests, crops, pastures, wildlife, lakes, wetlands, and rivers. This drought was evocative of the 1930s, but through improved land and water management and a stronger economy, its impacts on society were far less severe than that famous dry period. The hot sunny days, dust storms, cracked soil, snowless winters, and dry lakebeds burned their way into our collective memories and now have thankfully given way to a period of relative water abundance. But we know that drought will return again and that we must be prepared for it; we must understand it better, be better able to predict it, and must suggest alternatives to managing our farms, forests, and water bodies in the absence of sufficient precipitation.

The Drought Research Initiative concept was formed during the drought, but with the intention of providing new knowledge and predictive capability for the next drought. We all knew that something had to be done to use observations of this drought to create knowledge that would reduce the damage of the next drought. It has been a remarkable assembly of atmospheric scientists, hydrologists, hydrogeologists, foresters, and agricultural scientists focused on the recent drought on the Prairies, but with an eye to past and future droughts and the global reach of drought. The strong support and vision of the Canadian Foundation for Climate and Atmospheric Sciences provided the basis for DRI, and the investment of scientific expertise, data, and advice from Environment Canada, Agriculture and Agri-Food Canada, Natural Resources Canada, and every Prairie provincial government gave it the capacity to deliver substantial science and new predictive models in only five years. Thanks to those who contributed to DRI, we better understand how drought forms, evolves, and ends, why precipitation forms with such difficulty, how severe storms can still develop during drought, how drainage basins disconnect, snows sublimate, wetlands dry, soil moisture reserves evaporate and streamflows cease, how groundwater is not only unsustained but withdrawn in drought. We can now better calculate the connection between drought in the atmosphere, water on the ground, soil moisture, and groundwater during drought, and understand the limitations of our models and how they might be improved.

Drought is a gargantuan problem and it is our hope that DRI has made it a little smaller and somewhat more understandable, predictable, and manageable so that future generations dealing not only with drought but with the full effects of a changing climate can employ our knowledge and tools to mitigate its impacts on society and the environment. Finally, we hope that our model of collegial, interdisciplinary research can be used for future problems of water and climate in Canada.

# COMMENTARY

*James P. Bruce, Chair, Board of Directors, DRI Network*

The DRI Network was established, very wisely, by the Canadian Foundation for Climate and Atmospheric Sciences. This experience has left me with great appreciation for the imaginative scientific leaders Ronald Stewart and John Pomeroy, and for the whole entrained scientific community. They have accomplished much in a relatively short time. DRI also gave us the opportunity to lure Richard Lawford back to Canada as Network Manager. His coordination and leadership were crucial to DRI's scientific successes and effective management. Very valuable connections of Canadian work to related international activities have arisen from DRI, benefiting both Canada and communities abroad. Since I still think of myself as a hydrometeorologist, it was especially gratifying to see the close cooperation between hydrology and meteorology within DRI and the important advances made in modelling key processes through this cooperation.

One worrisome initial constraint on the programme, due to financial limitations, was the lack of funding for widespread application of DRI findings. However, through the efforts of the Prairie Farm Rehabilitation Administration (now the Agri-Environment Services Branch), particularly Harvey Hill, and the Saskatchewan Research Council, especially Elaine Wheaton, much progress was made in assisting farming and water communities in coping with drought and using DRI scientific insights.

In short, it has been a privilege to have a ring-side seat as a member of the Board of Directors to view the extraordinary accomplishments of the scientists and the initial applications of results. It is evident that DRI will leave a long-lasting legacy in scientific understanding and effective drought management.

# COMMENTARY

*Harvey Hill, Chair, DRI Partners Advisory Committee*

The primary objectives of the DRI project have been addressed in a manner that illustrates the ideal of scientific research. Hypotheses were tested via research and knowledge was extended with a whole set of new questions raised based on the knowledge gained. In addition, DRI has strongly contributed to developing the next generation of Canadian climate scientists.

One of the many highlights was the knowledge gained regarding the relationship between agricultural drought indices to wheat yield and quality data. More emphasis needs to be placed on indices derived from evaporative demand and water balances because they are more strongly correlated to wheat yield and quality than indices based on water supply (precipitation) alone.

A great deal was learned about the processes and resources required to successfully translate research into operational environments. For example, DRI's experimental linking of its databases and knowledge to drought vulnerability and adaptation simulations is an example of this transition.

Personally, the experience of being Chair of the Partners Advisory Committee provided a tremendous opportunity to understand the issues facing water managers on the Prairies and the research networks that exist to address those issues. The DRI effort has helped me gain a much greater understanding of the processes associated with drought and the factors that must be considered to translate this information into operational environments.

Most importantly, the people have been what has made this experience such a positive one. I want to thank Richard Lawford, Ron Stewart, and John Pomeroy for giving me the chance to participate in this process. I have formed friendships and working relationships that I believe will extend well into the future.

# COMMENTARY

*Richard Lawford, DRI Network Manager*

As the Network Manager for the Drought Research Initiative, it is a privilege to provide a brief perspective of the project. DRI has not only contributed to our understanding of drought on the Canadian Prairies; it has provided us with experience in innovative ways to conduct large-scale research projects. While case studies have been used to explore shorter-term events such as floods and tornadoes immediately after their occurrence, this approach has rarely been applied to climate anomalies such as multi-year droughts. In this project, DRI investigators have had access to better data than researchers carrying out most other drought studies because they started in 2006 immediately after the event, while memories of the impacts were still fresh and the data were still readily available. As a result, this study of a multi-year drought provided an opportunity to take precipitation anomalies and drought indices, variables that are often mere statistics in drought studies, and to give them greater meaning by relating them to hydrometeorological processes and socio-economic impacts. This study has also suggested that while the impacts of the drought were great, they would have been much worse had we still been using the technologies of the "dirty thirties". As the climate varies and changes, we need to remain vigilant of our industrial and technological development so that our land and water use policies and practices promote greater resilience rather than make society more vulnerable to drought.

There are many reasons for this project's success, including the scientific strength of investigators, the leadership of the Principal Investigators, Professors Ronald Stewart and John Pomeroy, and the tradition of Canadian collaboration between meteorologists and hydrologists that has grown over the past two decades, starting with the Mackenzie Global Energy and Water Cycle Experiment Study (MAGS). While this study made progress in integrating aspects of biological and social sciences with hydrology and meteorology, more work needs to be done before we can claim to have a fully functional multidisciplinary analysis framework for the physical and social dimensions of environmental research.

From my perspective, the DRI experience was a good reminder of the Canadian approach to scientific challenges. While it meant moving back to Canada from the USA, where the science community is much larger (not to mention the science budgets), it was encouraging to find that Canadian scientists are still very collaborative and ready to work together toward a comprehensive understanding on a specific research topic. The readiness of scientific leaders such as Jim Bruce and federal and provincial experts such as Harvey Hill, among many others, to engage in DRI was very gratifying. It was also good to see a number of graduate students develop as scientists and professionals through their involvement with DRI. While DRI will have many legacies, arguably none will be greater than the young people who have received training and research experience through its studies.

I would also like to thank Ronald Stewart for his guidance and support. I am grateful to him as well as John Hanesiak and David Barber for providing administrative services and office space at the Department of Environment and Geography and the Centre for Earth Observation Science at the University of Manitoba over the past four and a half years.

# INTRODUCTION

*Richard Lawford, Ronald Stewart, and John Pomeroy*

In September 2005, the Drought Research Initiative (DRI) was launched with funding from the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) to undertake a comprehensive study of the 1999 to 2005 drought. During the past six years, investigators from six Canadian universities have carried out studies on various aspects of the drought, documenting the history of the drought from its onset in Alberta and Saskatchewan in 1999-2000 to its final dissipation in Manitoba in 2004-2005. Their work was supplemented by the efforts of collaborators within Environment Canada and other federal and provincial government departments.

This report, *The 1999-2005 Canadian Prairies Drought: Science, Impacts, and Lessons,* gives an overview of significant findings of the DRI project. It was inspired by *The Full Picture*, a recent report prepared by the Group on Earth Observations (GEO) and Tudor Rose Press. In our report, the results of DRI research are described by the investigators and the collaborators who have undertaken the research. The research descriptions have been modified for general readership by Andrée-Anne Boisvert, our Technical Editor, so that the stakeholders and government departments who must cope with drought impacts can use this report in their planning and programme development.

Specifically, this report describes studies that have been undertaken by DRI to characterize the drought, to understand the underlying physical processes that accounted for its initiation, intensification, and eventually its demise, and to assess issues related to drought prediction. In addition, this report describes unfunded efforts that were devoted to considering the 1999-2005 drought in the context of other historical droughts and to exploring ways in which the DRI results and legacy could benefit stakeholders and government departments. Readers can distinguish between the contributions of investigators and collaborators because the biographies of funded investigators (those who received research funding from the DRI project) are marked by blue backgrounds, while the biographies of collaborators are marked by green backgrounds. The articles in this document include overviews, research related to atmospheric sciences, hydrological sciences, drought impacts and, finally, the DRI legacy in areas of data and user interactions. This introduction outlines a few highlights from the articles in each of these areas. Readers may wish to refer to the list of acronyms on page 106 to assist them in following the discussions in some of the articles.

## Overview Articles

Stewart et al. (page 5) provide an overview of the DRI framework and show how the different projects support its overall themes. As they note, CFCAS funded research on three core themes, while two other themes progressed on a "best efforts" basis. The research efforts in these five themes are described and the critical scientific questions associated with each theme are elaborated. The network aspects of DRI in building linkages both nationally and internationally are also described.

Hanesiak et al. (page 13) provide a synthesis of a wide range of analyses from climatological, hydrological, and agricultural perspectives, each aimed at quantifying some physical feature of the 1999-2005 drought. They describe the drought by bringing together the time sequence of events associated with the emergence and intensification of the drought and the many different products and perspectives on drought encompassed by DRI. The drought first appeared in Alberta in 1999 and spread over southern and central Alberta and Saskatchewan in 2000. Its development and intensification in 2001 and 2002 resulted from the interplay of macroscale atmospheric processes and smaller-scale hydrologic and atmospheric processes. In subsequent years the centre of the drought shifted and the intensity of the climatic, agricultural, and hydrologic impacts were generally less concentrated, although Manitoba Hydro reported record low flows in 2003.

Wheaton (page 23) provides a review of the economic and social aspects of drought impacts, particularly in 2001-2002. Not only does this review identify crop failures and other losses that amounted to a $5.8 billion drop in GDP for these two years, it also highlights how a multi-year drought can have greater impacts because of the loss of buffering capacity that occurs in the first year of the drought.

## Atmospheric Sciences

Based on an analysis of upper air circulation patterns, Bonsal (page 25) reports that these patterns had several modes, each mode having the effect of limiting moisture transport into the region. In general, the length and severity of 1999-2005 drought was affected by the northward-shifted jet stream and storm track, a western British Columbia meridionally-oriented ridge/trough couplet, as well as the positive phase of the Pacific North American Oscillation. He also found that the circulation patterns of the most intense drought years (2001 and 2002) were significantly different than those associated with the severe droughts of 1961 and 1988. He concluded that, while important, teleconnection patterns alone are insufficient to understand the formation and dissipation of droughts.

Shabbar (page 29) describes an extension of the analysis of teleconnection, atmospheric moisture, and stability patterns by examining the relationship between these patterns and Sea Surface Temperatures (SST). In particular, through the use of Maximum Covariance Analysis, he found that 80% of the squared variance of winter global SSTs and the following summer Palmer Drought Severity Index values over Canada were explained by three principal modes. This variance appeared to be associated with the Atlantic Multi-Decadal Oscillation, the El Niño-Southern Oscillation Cycle, and Pacific Decadal Oscillation patterns. The results suggest that the prediction of global ocean SST is foundational for seasonal precipitation prediction.

Szeto (page 35) quantified the spatial and temporal variability of water and energy budgets for the Prairie region, including the budget anomalies associated with the drought. During the peak of the drought in 2001 and 2002, the region was characterized by relatively weak moisture flux convergence into the area, resulting in reduced winter precipitation and spring snow cover. Furthermore, moisture from the Gulf of Mexico was notably decreased during the drought seasons. The reduced spring snow cover contributed to soil moisture deficits in the region during 2001 and 2002, which in turn led to reduced evapotranspiration during the growing season. In addition, stronger-than-normal subsidence associated with anomalously high pressure over north-western North America also led to weakened moisture transport from the Pacific Ocean.

Leighton and Greene (page 41) show that the regions with the most months with "dry" and "extremely dry" Standardized Precipitation Index values were concentrated in central and southern Alberta during the 1999-2005 drought. 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 months than the spring and summer seasons. Leighton and Greene also compared cloud-precipitation relationships from the Canadian Regional Climate Model (CRCM) with those from observations over the Prairies. In general, the CRCM generally performs well, with varying degrees of success for different parameters, although it simulates the precipitation patterns quite well.

Stewart et al. (page 43) report on their analysis of the flow of atmospheric water through clouds and precipitating systems to the surface within and adjacent to drought regions, focusing particularly on episodic events and issues such as 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. They examined the major June 2002 rainstorm, which changed extremely dry conditions over southern Alberta and Saskatchewan to above-average annual rainfall in less than 72 hours. They found that the rain was more intense because of the dry sub-cloud region presented in drought, which facilitated rapid evaporation of falling precipitation and in turn altered storm dynamics. Studies of other instances of heavy precipitation during the drought showed that such extremes were more common than expected on the basis of background climatology.

Based on his analysis of mean mixing ratios and temperature differences in cropped and urban areas in and near Edmonton, Alberta, Strong (page 47) describes the causes of wet/dry discontinuities in the boundary layer near cities that can influence summer convective processes. According to his analysis, these moisture gradients are sufficiently large that they represent virtual discontinuities in the atmosphere and can influence convective development.

Brimelow and Hanesiak (page 51) describe how they validated the Canadian Prairie Agrometeorological Model (PAMII) crop model and used it to estimate soil moisture and evapotranspiration. These outputs were used to monitor the development of the drought and to assess the impacts associated with plant available water. The assessment demonstrated that PAMII is skillful at modelling the day-to-day variability in evaporation; it is capable of capturing the difference in evaporation of two contrasting vegetation types; and it simulates the contrasting evaporation observed in wet versus dry years.

## Hydrologic Sciences

Advances in drought prediction have come primarily through the improvement of hydrologic models. Lin and Wen (page 55) report on the Variable Infiltration Capacity land surface macroscale hydrology model, which they calibrated for the

Canadian Prairies and applied for runoff and soil moisture estimates. Sixty years (1950-2009) of daily Soil Moisture Anomaly Percentage Index (SMAPI) maps were produced for the Canadian Prairie Provinces and the intensity of the 1999-2005 drought was evaluated by comparing SMAPI values from this period with those of other dry periods. SMAPI maps can effectively monitor droughts and can be used in combination with precipitation forecasts to predict soil moisture and drought conditions.

Pomeroy and Pietroniro (page 59) provide an explanation of the two hydrologic regimes that function on the Canadian Prairies during drought. The first regime involves the rivers that originate in the foothills and carry snowmelt waters from the mountains to the Hudson Bay. The second regime, frequently referred to as the "non-contributing area", has its own internal transfers and supports the very productive agriculture sector. However, the hydrological cycle in these non-contributing areas is highly dependent on the summertime rainfall regime. Recognizing these two regimes is important for understanding the effects of drought on the Prairie region in terms of the hydrologic response of different parts of the same basin to summer drought conditions. Pomeroy and Pietroniro have made considerable progress in modelling these processes. They introduce their hydrological model developments here and are now ready to couple these developments with Environment Canada's atmospheric models.

Van der Kamp and Hayashi (page 63) show that groundwater patterns and trends can be identified from the existing observation well records. In general, shallow groundwater levels respond to spring melt and then decrease during the summer due to evapotranspiration. In a few developed areas, however, groundwater levels steadily decreased due to over-pumping, particularly during the 1999-2005 drought. Deeper wells respond over much longer time scales and can be used to gauge longer climatological signals. This work demonstrates the need to consider the anthropogenic effects as well as meteorological forcing in water management during drought.

Woodbury (page 67) describes the development and application of gCLASS, a groundwater version of the Canadian Land Surface Scheme (CLASS), which was developed by his group in order to better represent the coupling between groundwater and the atmosphere in the Assiniboine Delta Aquifer. The gCLASS model was developed by improving CLASS (or Soil Atmosphere Boundary, Accurate Evaluations of Heat and Water; SABAE-HW) using BOREAS data and by conducting intercomparisons with the SHAW, CLASS, HYDRUS-1D, and HELP3 models. Currently the model simulates the effect of drought on the aquifer and provides an assessment tool for management studies.

Bruce (page 71) outlines the effects of droughts on the levels of the Great Lakes. Using the Palmer Drought Severity Index to represent the intensity of Prairie droughts, he found that drought often occurs in the Great Lakes Basin in the year following or even during the same year as a major Prairie drought. Droughts in the Great Lakes Basin affect the rate of evaporation, net basin supply, and lake levels. He also found that low water levels tend to lag Prairie droughts by one to two years and have a slow recovery. The study demonstrates how drought, increased climate variability, and a growing demand for water all act simultaneously to affect lake levels.

## Impacts

Bullock (page 75) describes a comparative study in which a large number of agricultural drought indices are correlated with wheat yield and quality data. Indices based on evaporative demand and water balance were more strongly correlated to wheat yield and quality than indices based on water supply (e.g., precipitation). This suggests that work is needed on water supply drought indices to support the assessment of agricultural drought impacts.

In his description of drought implications for the Canadian Carbon Program, Amiro (page 81) reports on flux tower measurements over the Canadian Prairies and compares the fluxes over different vegetation types during the drought of 1999-2005. This analysis indicates that aspen stands are more vulnerable to drought conditions than grasslands, jack pine forests, and young forests. This finding suggests that aspen could be quite vulnerable to the effects of climate change.

Hogg (page 83) documents the effects of the extension of drought into boreal forest areas by relating monthly and annual Climate Moisture Index values to aspen growth and dieback features. Although forests respond more slowly to drought than grasslands and agricultural zones, substantial impacts on forests were recorded following the 2001-2002 drought, when severe dieback and mortality of aspen forests occurred across a large area of the parkland. Droughts such as the one in 1999-2005 have implications for Canada's wood fibre supply and forests' ability to uptake $CO_2$.

Sauchyn (page 87) reports on the use of dendrochronological studies to show the history of drought and streamflow. In addition to the 1999-2005 drought over the Canadian Prairies, other droughts and streamflow deficiencies can be found in the dendrochronology records for the 1920s, 1930s, and 1980s. However, droughts lasting for decades occurred further back in this record, during the 1500s and 1800s. The results of this historical analysis underline the need to strengthen the adaptive capacities of the agricultural and water resource sectors.

## DRI Contributions to Data Legacy, Outreach, and Policy

Harder and Constanza (page 89) describe the DRI data system developed as part of the DRI legacy. The system utilizes a hybrid computer system with both centralized and decentralized components, and will provide an archive for metadata on all DRI datasets as well as many of the datasets themselves. The interface to this system will function as a data portal by enabling investigators and users to access all of the DRI datasets and data products. The article describes the ongoing services provided by the data managers and their efforts to put a legacy data system in place before DRI's research efforts conclude.

Pittman et al. (page 93) summarize a unique collaborative effort between DRI and Agriculture and Agri-Food Canada (AAFC). They developed tabletop exercises to engage stakeholders and other users in simulations, whereby they used scenarios of drought conditions to make decisions about ways to adapt to the dry conditions. The Drought Early Warning System provided feedback on the relative usefulness of DRI research products and ways to standardize them so they would be easier to use. The drought preparedness part of the study, which supported AAFC interests, showed that users place a high priority on information as a central element of drought preparedness. They believe that during the past decade information has improved in terms of its availability, quality, and timeliness.

Lawford (page 97) describes aspects of drought research results in terms of their potential to inform policy options related to sustainable development. Responses can occur at the daily to weekly time scales for farm operations, at the monthly to seasonal for strategic responses by producers and agribusiness, and at years to decades for governments. In order to support sustainable development in times of drought, future research projects should focus on seasonal prediction, adaptive responses, and risk management to address the non-stationarity of the climate.

## Summary

The results from the Drought Research Initiative have been impressive given the moderate level of financial support it received and the size of the Canadian research community. The DRI management team, including the DRI Science Committee, has been able to mobilize this level of enthusiasm in the research community because drought is recognized as an interdisciplinary scientific and socio-economic issue of great concern to Canadians, especially to the agricultural and water resources communities of Western Canada. They have done it in a way that has exemplified the strategies that CFCAS has promoted in its networks, namely the training of highly qualified personnel, community-building, and public outreach from research networks. The leadership provided by DRI's Science Committee, its Board of Directors, and its Partners Advisory Committee has also been a strength for the Initiative. The largest tribute, however, must go to the investigators and collaborators who engaged in the research programme and did the creative thinking, modelling, analysis, and synthesis needed to generate the results that are presented in this report. We hope that as you read through this report you will see how our research results have contributed to a better understanding of the drought phenomenon and climate variability, and how these findings can support the more effective management of the renewable resources that are so critical for the Prairie economy.

*Overviews*

# A DROUGHT RESEARCH INITIATIVE FOR THE CANADIAN PRAIRIES

*Ronald Stewart, John Pomeroy, and Richard Lawford*

*Ronald Stewart has been a Professor in and Head of the Department of Environment and Geography at the University of Manitoba since July 1, 2008. Dr. Stewart obtained his B.Sc. (Honours) in Physics from the University of Manitoba and his Ph.D. in Physics from the University of Toronto. He conducted postdoctoral research at the National Center for Atmospheric Research (Colorado) and was an Assistant Professor at the University of Wyoming before moving back to Canada. He was a senior scientist with Environment Canada and an Adjunct Professor at York University in Toronto before moving to McGill and becoming a Professor in the Department of Atmospheric and Oceanic Sciences. Professor Stewart's research focuses on extreme winter and summer weather, precipitation, and regional climate. He has led numerous Canadian and international research activities addressing these issues. He conceived and is currently co-leading the Drought Research Initiative. Professor Stewart has also been President of the Canadian Meteorological and Oceanographic Society and he led Canada's involvement in the International Union of Geophysics and Geodesy for several years. He is a member of the international Global Energy and Water Cycle Experiment Scientific Steering Committee. He has also led global initiatives on regional climate within the World Climate Research Programme and is currently a leader within a new effort examining hydrometeorological extremes, including droughts and flooding, around the world. He is a Fellow of the Royal Society of Canada and the Canadian Meteorological and Oceanographic Society.*

## Background

Drought is a fundamental aspect of the global water cycle. Drought events do not necessarily lead to an overall change in the magnitude of the global water cycle, but they affect the regional cycling of water. Droughts are recurring aspects of weather and climate extremes, as are floods and tornadoes, but they differ substantially since they have long durations and generally lack easily identified onsets and terminations.

Drought can be considered an aberration within the atmospheric, surface, and sub-surface cycling of water and energy (Figure 1). This anomaly is initiated through large- to regional-scale atmospheric processes. It is enhanced and maintained through regional to local atmospheric, surface hydrology, land surface, and groundwater feedbacks, which operate at various time scales over the growing season and dormant snow-free and snow-covered periods.

Geographically, drought is a relatively common feature of the North American and Canadian climate system and all regions of the continent are affected from time to time. However, it tends to be most common and severe over the central regions of the continent. The Canadian Prairies are therefore prone to drought, as evidenced by the historical record (Figure 2).

Droughts on the Canadian Prairies have their own unique features. The large-scale atmospheric circulations are influenced by blocking from high terrain to the west and long distances from all warm ocean-derived atmospheric water sources; growing season precipitation is generated by a highly complex combination of frontal and convective systems; seasonality is severe and characterized by relatively long snow-covered and short growing seasons; local surface runoff is sometimes dominated by snowmelt water; there is substantial water storage potential in the poorly drained, post-glacial geomorphology; and aquifers are overlain by impermeable glacial till, although there are also important permeable aquifers in surficial deposits that have substantive water exchange with the surface.

A major multi-year Prairie drought began in 1999. Its atmospheric component ceased in 2004 and 2005 and many of its hydrological components ceased in 2005. This long-lived drought raised major concerns about the causes and potential impacts of these events.

Although some previous droughts were more severe when considering the whole Prairie region (Figure 2), the 1999-2005 event produced the driest conditions in the historical record over some parts. An illustration of the severity is shown in Figure 3 for the 2000-2001 agricultural years. Well-below-normal

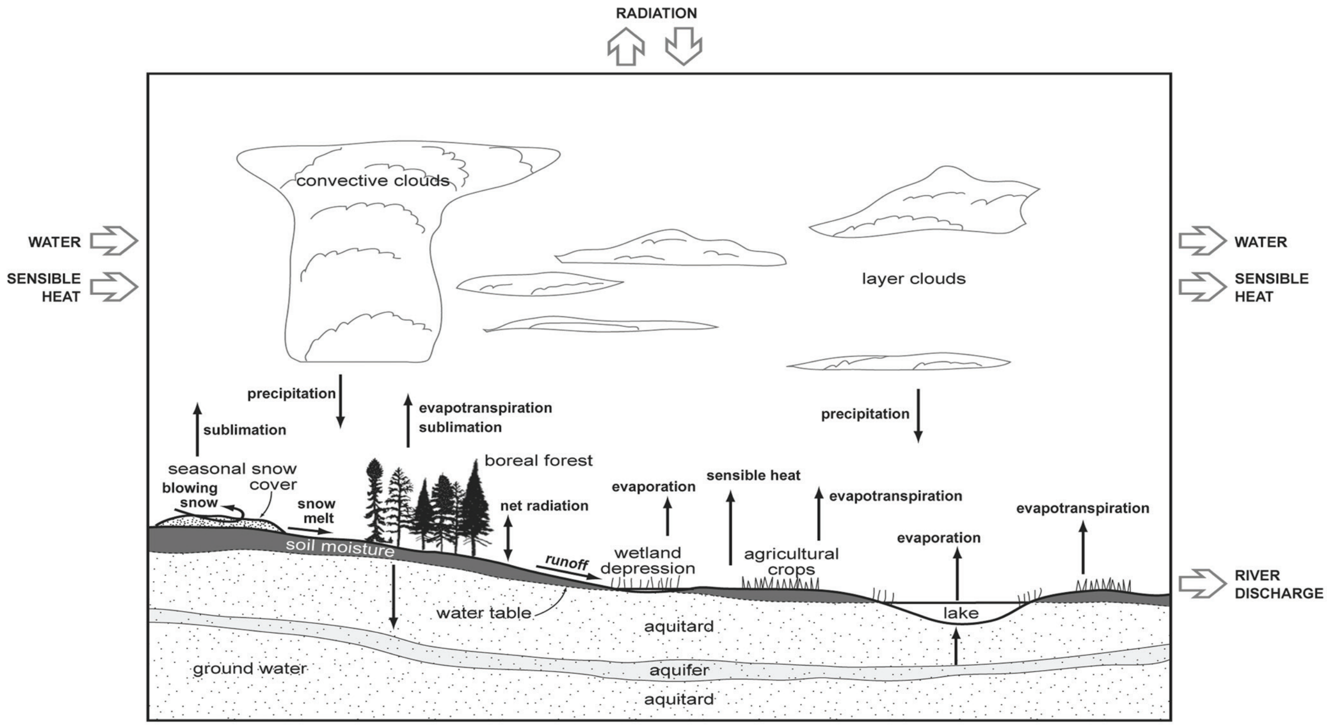

**Figure 1**. Water and energy cycling associated with Canadian Prairie drought.

precipitation was reported in parts of Alberta and Saskatchewan for more than four consecutive years, extending from the autumn of 1999 to the spring of 2004. According to Phillips (2002), for the western and central Canadian Prairies during 2001 and 2002, “it was the worst of times. Even in the dust bowl of the 1930s, no single year between Medicine Hat, Kindersley and Saskatoon was drier than in 2001. Astonishingly, Saskatoon was 30% drier this year than any other over the last 110 years”. The 1999-2005 drought affected agriculture, recreation, tourism, health, hydro-electricity, and forestry across the Prairies. The Gross Domestic Product fell by approximately $5.8 billion and employment losses exceeded 41,000 jobs for 2001 and 2002. This drought also contributed to a negative or zero net farm income for several provinces for the first time in 25 years (Statistics Canada, 2003), with agricultural production over Canada dropping by an estimated $3.6 billion at its peak in 2001 and 2002. Previously reliable water supplies such as streams, wetlands, dugouts, reservoirs, and groundwater were placed under stress and often failed. The number of natural Prairie ponds documented in May 2002 was the lowest on record.

Although the worst drought conditions occurred on the Prairies, the drought actually affected all regions of Canada. For example, in 2003, the dry interior of British Columbia experienced massive fires, including a major fire near Kelowna. The water levels of the Great Lakes were very low during this period, which had major impacts on shipping, tourism, and other sectors. The Maritimes also suffered from the effects of low water levels.

Despite their enormous economic, environmental, and societal impacts, there has never been a coordinated and integrated drought research programme in Canada. Given the importance of these extreme events, it is critical that they be studied appropriately with a view to better anticipate their occurrence and nature on short- and long-term scales. Given the magnitude of this task, it was decided that the first step would be to focus mainly on the Prairies.

## Objectives

The Drought Research Initiative was established to begin to address these drought-related issues. DRI is a research network that has been largely funded by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS). It also relies on support from in-kind contributions from many government departments.

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.

To address this overall objective, the network has focused on five research objectives/themes:

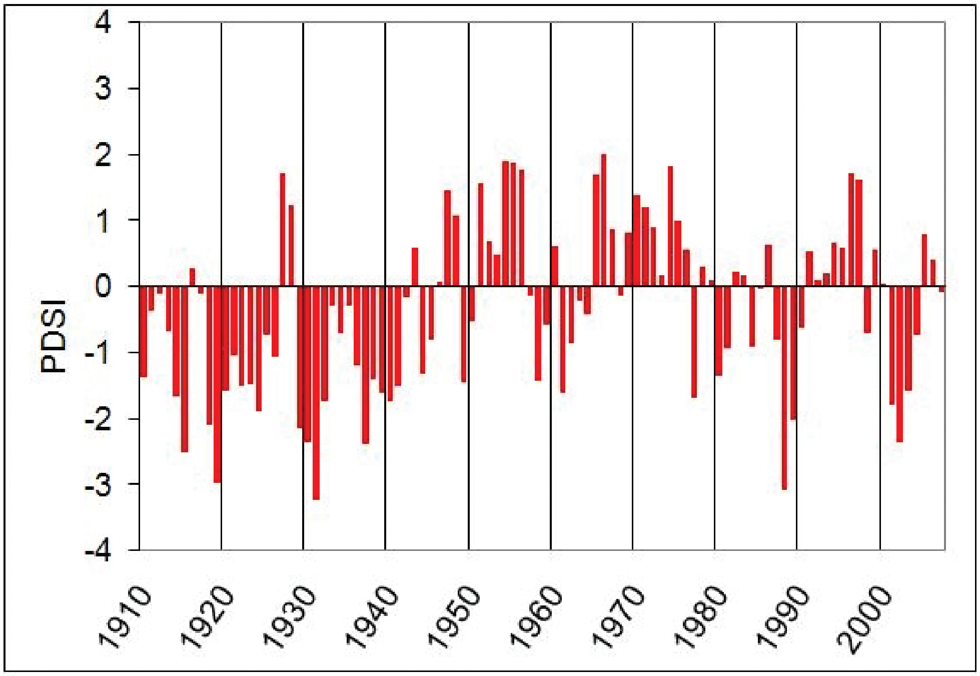

**Figure 2**. The annual average of the Palmer Drought Severity Index (PDSI) for the Canadian Prairies over the 1910-2007 time period. This figure is based on an average of 15 weather stations across the southern Prairies. PDSI values less than zero are indicative of dry conditions and PDSI values greater than zero are indicative of wet conditions.

- 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
- Apply our progress to address critical issues of importance to society

DRI has brought together a large number of university and federal and provincial government researchers to address this issue in a fully interdisciplinary manner with expertise encompassing the atmospheric, hydrologic, land surface, and predictive aspects of droughts on a variety of spatial and temporal scales.

Over its five-year period of existence, DRI has focused primarily on the recent drought over the Prairies. It was by far the best observed and modelled drought over this region and its impacts are still fresh in peoples' memories. The strategy of focusing on physical processes and particular time periods or events is a common one, although not often used for drought research. The assumption is that it is generally often only feasible to bring together for a particular event or period the necessary full complement of observations, models, and scientific research capability to examine phenomena such as drought. In DRI's case, one can even consider the focus on 1999-2005 a pilot project for drought research which included strong interactions with those affected by it.

From a longer-term perspective, it is envisioned that this five-year network represents an essential step toward our ultimate goals:

- 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

These two overarching goals directly address major issues for society. There needs to be better guidance on the likelihood of drought for more effective planning; this must include its detailed and varying structure. Furthermore, there is tremendous concern that our changing climate will lead to more periods of drought in the future over the interior of North America (see for example Lemmen et al., 2008). The implications of this are so far-reaching that our ultimate objective must be to better assess the likelihood of such a scenario. This research network allows us to move systematically toward these two objectives.

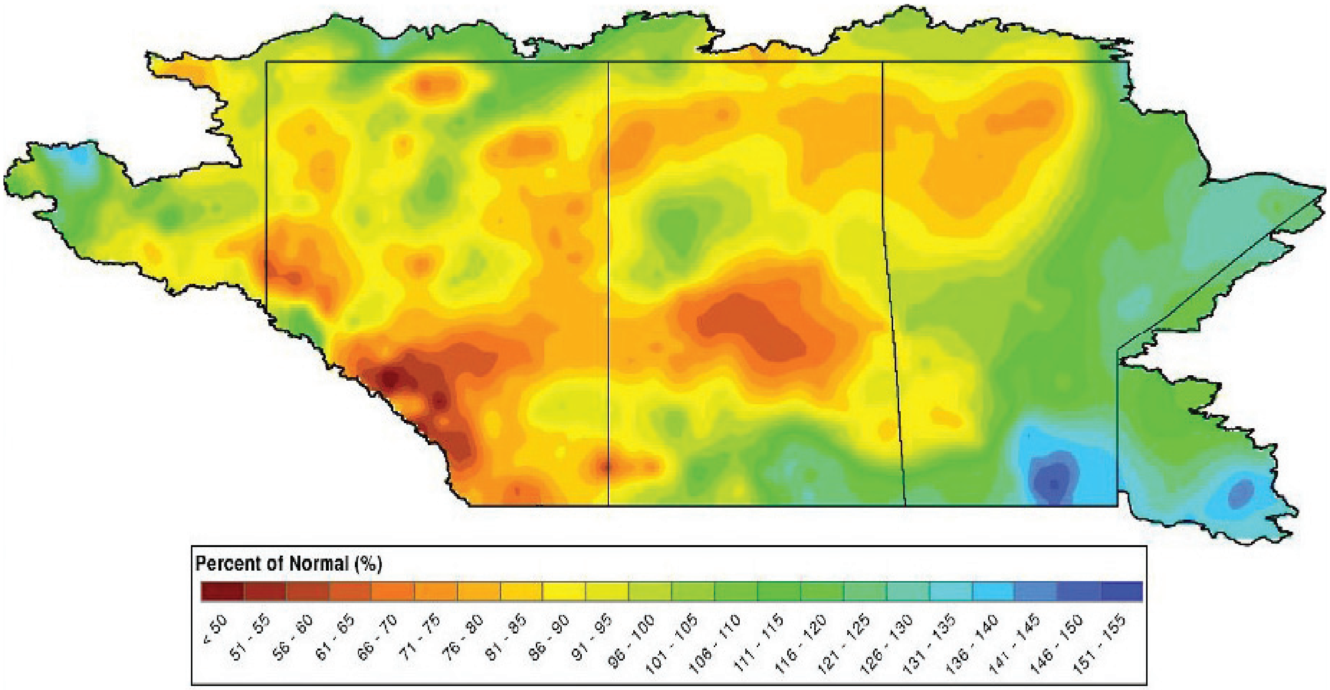

**Figure 3**. Example of precipitation deviation from normal in the early drought period, September 1, 2000 to August 31, 2001. A number of locations broke all-time low precipitation records in 2001 or in other years of the drought.

This article provides a brief overview of DRI in the context of its contributions to science and practical resource management. It also provides a framework for the subsequent articles which address the rich research results of DRI-funded projects.

## Strategy

As outlined above, DRI is achieving its overall objective through a focus on five complementary, cross-cutting research objectives or themes. The five themes represent a logical sequence for such a network by including the quantification, understanding, and better prediction of a particular drought, and the subsequent comparison of our findings with other droughts as well as the articulation of their implications for society.

## Theme 1

The first step towards achieving a better understanding of the 1999-2005 drought involves the quantification of its atmospheric, hydrologic, and land surface features on a variety of spatial and temporal scales. This information is an important foundation and forms much of the basis of Themes 2 through 5.

Theme 1 addresses three focused questions, namely:

- What variables are required to quantify the characteristics of this recent drought?
- What data sources and model outputs are available for quantification of these parameters?
- How do we characterize and "close the budgets" of water and energy over the Prairies?

The quantification of drought necessarily means that many fluxes and reservoirs need to be examined. This is schematically illustrated in Figure 1. In particular, variables characterizing atmospheric, surface, and sub-surface states are required. A three-dimensional assessment of the atmosphere during drought over various temporal scales requires, for example, knowledge of temperature, humidity, geopotential height, wind, clouds, precipitation amount, and current weather. The transfer of heat and moisture between the surface and atmosphere must also be assessed. At the surface, the spatial and temporal characteristics of vegetative state (in terms of water stress) for major vegetation types (crops and boreal zones), soil moisture, stream network, river flows, lake levels, wetlands, and depression storage are required to assess when and where drought is occurring. Sea Surface Temperatures are also needed to characterize global connections with Prairie drought. The spatial characteristics of groundwater and sub-surface moisture will also be an important long-term indicator of drought.

It is not easy to acquire the needed observational information. First, operational instrumentation across the region are in some cases arranged as observational networks. This includes weather stations, radars, lightning detectors, stream gauges, lake levels, vegetation assessment, crop yields, snow information, soil moisture, and groundwater. In general, though, relatively few of these sites exist. Others, however, have used some of these data in order to make gridded products that are extremely useful for characterizing drought. One example is the precipitation information CANGRID, derived from station information. Second, satellite-based data are extremely important and provide critical information on a host of variables in the atmosphere, at the surface and even sub-surface. Variables range from clouds and precipitation to snow cover and vegetation, down to sub-surface water storage. Not all of the products are reliable, however, and many have limitations due to temporal and spatial resolution. Third, there are only a few locations at which a large number of detailed measurements are carried out. This includes Boreal Ecosystem Research and Monitoring Sites (BERMS) in Northern Saskatchewan, the St. Denis Wildlife area near Saskatoon, and the Assiniboine Delta Aquifer in western Manitoba. Fourth, some individual researchers have acquired their own unique field measurements. These special datasets can be accessed by contacting the researcher directly and are being incorporated into the DRI data legacy archive.

An additional issue for the Prairies is that they are covered by undulating or hummocky terrains with numerous topographic depressions. The majority of individual depressions are too small to be captured in 1:50,000 topographic maps, but collectively they represent an enormous capacity to store surface water without allowing it to drain into streams. Proper characterization of depression storage is essential for understanding the hydrology of the Prairie region.

Use is also being made of model products. This includes analysis and prediction products from, for example, the Global Environmental Multiscale model (GEM), the National Centers for Environmental Prediction (NCEP), the European Centre for Medium-Range Weather Forecasting (ECMWF), the Canadian Regional Climate Model (CRCM), and the Canadian Centre for Climate Modelling and Analysis (CCCMA). Each of these models has its own spatial and temporal resolution, from large spatial scales (of the order of a few hundred kilometres) to shorter mesoscale ones (a few kilometres). Hydrologic and land surface models are just as critical for DRI. These include the Modélisation Environnementale Communautaire (MEC) Surface and Hydrology Model (MESH), which is linked with GEM, the Variable Infiltration Capacity (VIC) model, and the Cold Regions Hydrological Model (CRHM).

Furthermore, the fluxes and budgets of water and energy throughout and within the Prairies during drought must be addressed. This needs to be accomplished through analysis of the model and observational products described above. This DRI-wide activity needs to be accomplished on scales ranging from long-term values over the entire Prairies to smaller scales (less than a month) over smaller domains that experienced different degrees of impact.

### Theme 2

Theme 2 addresses the need to better understand the processes and the feedbacks responsible for the drought's initiation, persistence, and termination. In particular, it answers the following questions:

- What processes were responsible for the onset of the recent drought?
- What processes and feedbacks contributed to the drought's evolution, persistence, and spatial structure?
- What processes and feedbacks controlled the termination of this drought?

Much of DRI's effort is devoted to better understanding drought processes and feedbacks. Prairie drought processes have characteristic spatial and temporal scales. These are shown in Figure 4, in which vertical spatial scale is plotted with horizontal spatial scale and temporal scale. We hypothesize that atmospheric teleconnections normally induce the onset of drought, but the termination of drought is linked with land surface and groundwater conditions as well as atmospheric conditions. It is also important to note that land surface hydrological and/or biophysical processes generally operate at small spatial scales (and with larger inherent spatial variability) and that there is a hierarchy of atmospheric process scales. The horizontal scale link between land surface and groundwater processes (which produce many of the greatest societal impacts) and the large atmospheric scale is provided by a cascade of atmospheric processes and by large basin streamflow. Overall, however, the evolution of drought across different scales is not well understood, and DRI is directly addressing this issue.

There are many ways in which drought, essentially a sustained precipitation deficit, can be prolonged. Some of the factors that reduce precipitation would include, for example, large-scale circulation anomalies, lack of moisture advected into a region, reduction of local moisture supplies, production of virga instead of precipitation, and possibly even the reduction of precipitation by enhanced aerosol concentrations due to blowing dust. There is evidence that these and numerous other factors were operating at various times and locations during this more than five-year-long drought period, preventing substantial precipitation from being produced over large regions of the Prairies.

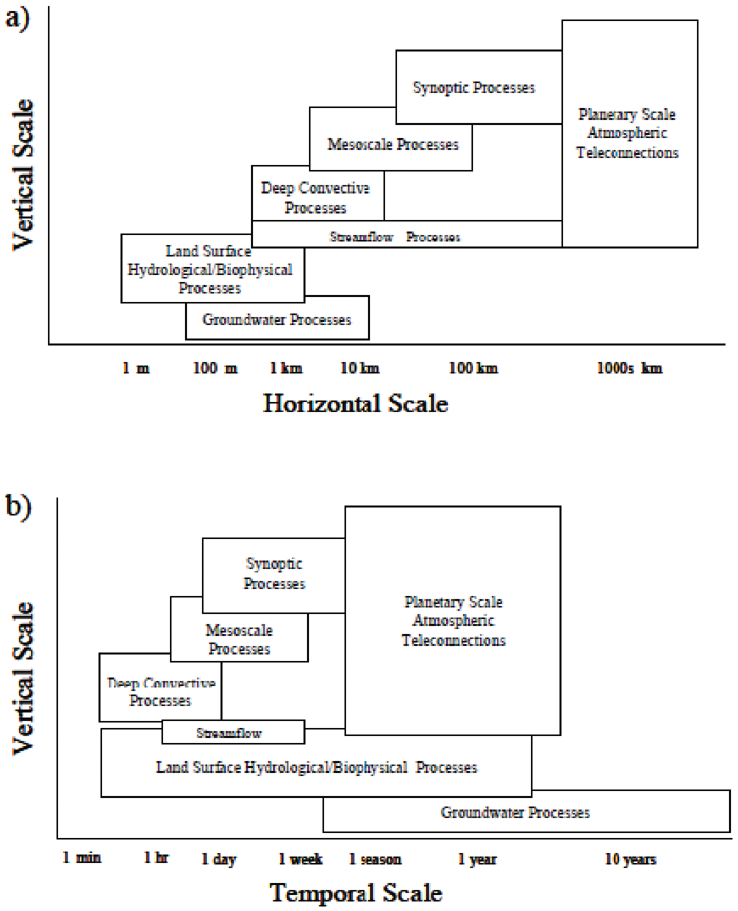

Figure 4. (a) Spatial and (b) temporal scales of processes associated with Prairie droughts. Note that "mesoscale" refers to atmospheric mesoscale processes, including the precipitation associated with frontal systems.

## Theme 3

Given that the 1999-2005 drought and its features have been characterized and the fundamental responsible processes better understood, the next step is to assess and improve drought prediction techniques. The modelling tools used are global and regional climate models (GCMs and RCMs) and hydrological models. The hydrological models are driven by output from the atmospheric models, ongoing research sites, and available reanalysis data. Atmospheric modelling spans global and regional scales to watershed scales characteristic of the Prairies. Hydrological modelling is accomplished using a hierarchy from small-scale detailed process models to macro-scale distributed hydrological models and groundwater models run over river basins. This theme addresses the following major questions:

- How well was the current drought predicted based on current techniques?
- To what extent could this prediction be improved through better initialization?
- To what extent could this prediction be improved through dynamical downscaling and better physics?
- What are the appropriate scales and processes for prediction of Prairie droughts?

Use is being made of archived information to address many of these issues. The difference between DRI-related work and that of other drought projects is that DRI focuses on a particular extreme and examines many more variables beyond temperature and precipitation. In particular, these studies illuminate the effects of precipitation deficits as they propagate through surface and sub-surface hydrology systems.

## Theme 4

Given that the 1999-2005 drought and its features have been quantified, this event can be more readily compared to occurrences at other times and in other locations. The objectives of Theme 4 are being realized through the following research questions:

- How do the physical features, processes, and feedbacks of the recent Canadian Prairie drought compare with a) previous droughts over the Canadian Prairies, b) Canada-wide droughts, c) U.S. Great Plains droughts, and d) droughts across the world?

- How does the prediction of the recent drought compare with predictions of other droughts?

- How does the recent drought compare with past climate variability and projected climate change?

Bonsal (2008) identified a number of aspects of the recent drought in relation to previous droughts. It needs to be recognized that this includes the internal structure of drought, not just its presence over a particular region. Many droughts, such as the 1999-2005 one, illustrated a complex internal structure to precipitation patterns which changed dramatically during the drought. Such internal features can in some instances be just as important as the general occurrence of drought. In order to meet the needs of many user groups, it is evident that such comparisons need to include many more variables and processes in the atmosphere and on the surface than normally addressed.

### Theme 5

This theme, which deals with the social, economic, and environmental aspects of drought, can be broken down into the following sub-issues:

- Which organizations are affected by drought?

- What is the exact nature of their impact and how can it be alleviated?

- Given the progress being made by the network, how can it address drought impacts on affected organizations?

The development of an understanding of drought impacts requires extensive interaction with users. Information on the impacts of drought has been gathered through interviews, exchanges in provincial user workshops, and through the Partners Advisory Committee (PAC). The progress made by DRI has been conveyed to impacted groups through publications, seminars, and interactive meetings. Through this theme, impacted groups in turn informed the network on critical issues, thresholds, and other factors relating to drought. User interactions through the Drought Early Warning System (DEWS) have also expanded DRI outreach. This information in turn affected the nature of DRI itself. These issues are addressed in more detail in Lawford et al. (2008).

### Linkages

Whereas previous studies have focused on individual features occurring over the Prairies (e.g., large-scale circulation, storms, land surface processes, and river flows), DRI focused on the entire system during periods of extreme dryness. Even though there are several international and, to a lesser extent, national programmes that have addressed extremes in the water cycle, this is the first study to focus on the Canadian Prairies.

### Canadian Linkages

On a research level, the network has brought together a number of university-based researchers from institutions across Canada as well as organizational units and experts from many federal and provincial agencies and departments. At the federal level, it has also established collaborative links with several components of Environment Canada, Agriculture and Agri-Food Canada, and Natural Resources Canada. DRI has also established close links with the Canadian Group on Earth Observations (GEO), which is very interested in drought. DRI can be considered as a test-bed for some of their long-term plans.

DRI has also established many linkages at the provincial level. Within the Prairie Provinces, this includes Alberta Agriculture Food and Rural Development; Alberta Environment; Manitoba Agriculture, Food and Rural Initiatives; Manitoba Hydro; Manitoba Water Stewardship; Prairie Adaptation Research Collaborative; Saskatchewan Agriculture; Saskatchewan Environment; Saskatchewan Watershed Authority; Sask Water; and the Saskatchewan Research Council. Linkages also include the Prairie Provinces Water Board, which considers water flows across provincial boundaries, and the Western Water Stewardship Council, which plans water management for the Prairies over the coming decades. Links have also been established with Ouranos, the Quebec-based initiative concerned with regional climate.

The DRI Network complements previous or current Canadian research studies, including the Mackenzie Global Energy and Water Cycle Experiment (GEWEX) Study (MAGS), which examined Mackenzie basin water and energy cycle issues (Stewart et al., 1998), and Canadian Climate Variability and Predictability (CLIVAR) activities, which considered climate variability (Derome et al., 2004). DRI has also established links with a recently initiated major project on institutional adaptation to climate change, especially water scarcity issues (a collaborative research initiative led by the University of Regina).

### International Linkages

DRI has established linkages with many drought studies in the

United States. The western portion of the U.S. has also been experiencing drought conditions for several years and there is an increasing sense that a more coordinated effort is needed to address drought (Western Governors' Association, 2004). Although there is not yet a comparable U.S. drought network, strong linkages have been developed with U.S. GEWEX-oriented studies. The network is also interacting with the U.S. Drought Mitigation Center, the North American Drought Monitor, and U.S. CLIVAR activities.

DRI is also contributing to and taking advantage of research in other parts of the world. Both the World Climate Research Programme (WCRP) and GEWEX have recently initiated activities focusing on extremes such as droughts. The work done by the DRI Network directly contributes to these efforts and may even be considered a model for addressing extremes in a comprehensive manner. Other collaborations include the International Decade for Predictions in Ungauged Basins (PUB) 2003-2012, a hydrological decade for improving the understanding and prediction of hydrological systems where surface observations are not available for model calibration. PUB particularly emphasizes hydrological prediction in semi-arid to sub-humid zones. Through exchange of techniques and information, DRI both contributes to and benefits from links to PUB. DRI has also contributed to the 2009-2011 work plan of the Group on Earth Observations (GEO) through its support of a task on regional drought impacts and the activities of the GEO User Interface Committee.

## Summary

Drought is a major economic and environmental issue for Canada and DRI is addressing it in a comprehensive manner for the first time. This collaborative effort provides a better understanding of Prairie droughts' physical features, the processes that control them, and our ability to predict them. DRI is developing an understanding of the full spectrum of droughts by comparing the recent 1999-2005 Prairie drought with other droughts occurring elsewhere. Furthermore, interactions with the user community have enabled DRI to be more responsive to the information needs of those impacted by drought.

DRI has brought together many perspectives on drought. Although the project came to an end in 2011, it is expected that other future initiatives will take up the critical challenge of monitoring, predicting, and responding to drought. The comprehensive approach used by DRI can be applied anywhere in Canada and, indeed, the world, to address drought as well as other types of extremes.

Thus, a comprehensive study of drought throughout Canada is coming to an end. This project has brought together researchers from several disciplines and collaborated with many partners affected by drought. The many articles gathered in this publication represent one measure of this progress. DRI has made a difference.

*Overviews*

# PHYSICAL CHARACTERIZATION OF THE 1999-2005 CANADIAN PRAIRIE DROUGHT

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## Introduction, Background, and Motivation

The 1999-2005 drought has been highlighted as a significant event from many vantage points and was one of the driest meteorological and hydrological events on record. It was quickly followed by a pluvial period in 2004 and 2005 over parts of the drought-affected area. The two contrasting periods (drought versus pluvial) offered a unique opportunity to examine their physical differences. The drought had major widespread socio-economic impacts (see Wheaton, this volume). The major considerations that arise after any drought are: which regions were affected; why it occurred; and why it lasted as long as it did. As a first step to answer these important questions, a general physical characterization of the drought must take place. A detailed examination of the atmospheric conditions that took place during the drought needs to be undertaken. A similar analysis would also be necessary for surface state and its evolution, including vegetation and surface hydrology. Lastly, a detailed look at sub-surface characteristics such as groundwater is also necessary. All three of these facets of drought (meteorological, agricultural, and hydrological) are ultimately tied together by various two-way feedback mechanisms. A detailed look into the evolution of these characteristics over various time scales must therefore be included in the analysis. The analyses are also critical to better monitor drought once it has begun.

This article highlights the main physical atmospheric, surface (vegetation and surface hydrology), and sub-surface hydrological characteristics of the 1999-2005 period in order to better understand the drought's spatial and temporal character and examine the continuity (or otherwise) of the various data and model products available to assess the physical make-up of drought – an important consideration for drought-monitoring in the future. The characterization analysis shown here highlights the complex nature of drought's spatial and temporal patterns, as not all regions experienced drought over the entire period, and there were many instances of sharp gradients between wet and dry areas.

## Methodology

In order to tackle the task of characterizing drought, a systematic and somewhat chronological approach was adopted. First, the variables and parameters required to characterize the meteorological, agricultural, and hydrological drought were listed. Second, the data sources and model outputs were identified to quantify these variables and parameters. After this was accomplished, all available datasets were analyzed appropriately, depending on the nature of the data (i.e., one-dimensional time-series data versus two- or three-dimensional time-dependant data). Examples of these analyses follow in forthcoming sections. A chronological analysis approach was adopted to examine how the drought varied in space and time. This also allowed for easier comparisons amongst datasets. Various space and time scales were used depending on the dataset limitations and intended purpose of the analysis.

In many instances, issues with data gaps, standardization, and determining the “correct” or “best” data source were encountered. For example, station precipitation data can contain errors for a variety of reasons. Suspect data must be corrected, if possible, or discarded. There have been various attempts to correct precipitation data and minimize the effects of missing data, station relocation, gauge changes, and others by producing statistically sound daily, monthly, and seasonal averaged data for individual stations and spatially gridded products (e.g., CANGRID, Mekis and Hogg, 1999; ANUSPLIN, McKenney et al., 2006). In some cases, more than one dataset was needed to characterize a particular variable. This typically resulted in interesting comparisons and allowed for an “ensemble” approach to the analysis. In many cases, determining the “correct” or “better” dataset was not possible. It was also determined that the drought must be put into some context. For example, in the case of precipitation, in order to quantify any particular drought, one must compare precipitation during that drought period to some climatological time period – essentially an anomaly analysis, either in percent of “normal” or negative/positive amounts below/above the climatological average. The climatological “normal” period depended on the total length of quality data available.

## Atmospheric Characteristics

The annual progression of the meteorological drought varied spatially from 1999 to 2005 with a belt of abnormally low precipitation (50 mm to 150 mm less than normal) across the northern Prairies in 1999 and 2000, which then became much more widespread in 2001 and 2002 (maximum precipitation deficits greater than 150 mm in both years; Figure 1). During the peak of the drought in 2001 and 2002, the region was characterized by relatively weak moisture convergence, or piling up of moisture (not shown) into the area during the winter and summer. This resulted in reduced winter precipitation and spring snow cover, and less precipitation in summer (Szeto, 2007; Szeto, 2010). In 2003, much of Alberta and extreme south-west Saskatchewan experienced near-normal to greater-than-normal annual mean precipitation, with the remainder of the region being less than normal (up to 150 mm less than normal in east-central and northern Saskatchewan and northern Manitoba). The above-average precipitation swath in extreme southern Saskatchewan and south-east Alberta in 2002 was mainly due to a single extreme summer large-scale weather system with embedded thunderstorms that took place over a two- to three-day period (see Stewart et al., this volume). In addition, sharp spatial gradients in annual and seasonal precipitation were common in almost every year, particularly in summer, due to the nature of small-scale (thunderstorm) events. For example, in 2002, south-west Saskatchewan had greater-than-normal annual precipitation of more than 300 mm, while just one hundred kilometres away, to the north-west, a deficit of annual precipitation of more than 150 mm occurred. This illustrates the complex nature of meteorological drought characteristics and how the large- and smaller-scale atmospheric behaviour can define drought areas from non-drought areas, even when they are in close proximity to each other. In contrast, 2004 and especially 2005 saw much greater precipitation amounts than normal (maxima of greater than 200 mm in 2004 and greater than 275 mm in 2005) in southern Alberta and southern and central Saskatchewan and Manitoba. Central and northern Alberta and northern Saskatchewan, however, still experienced below-average precipitation in 2004 and 2005.

Statistical analysis of the spatial pattern of annual and seasonal temperature departures from normal reveals that there is no clear relation between above-normal temperatures associated with lower precipitation area, or vice versa (not shown). Annual mean temperature departures from normal varied widely over the drought period, with 1999 being largely above normal over the Prairies but warmer (+2°C to +3°C) in the eastern half of the domain, while 2000 was about normal in most regions, but once again slightly warmer in the eastern Prairies. In 2001, most areas were only slightly above normal (0°C to +1°C), with northern Manitoba and northern Saskatchewan being +2°C to +3°C warmer than normal. In contrast, 2002 was cooler than normal in most areas (0°C to -2°C) except for north-east and extreme southern Manitoba, which was slightly above normal (0°C to +1°C). Temperatures were near normal over the Prairies in 2003 except for parts of central and northern Alberta (-1°C to -2°C) and northern Manitoba (+1°C to +2°C). In 2004, the extreme western half of the Prairies was slightly above normal (+1°C), while the eastern half was below normal (-1°C). The entire Prairie region had above-normal temperatures in 2005, with anomalies ranging between +0.5°C to +1.5°C.

The precipitation and temperature patterns discussed above are quite different than those observed during other droughts in the

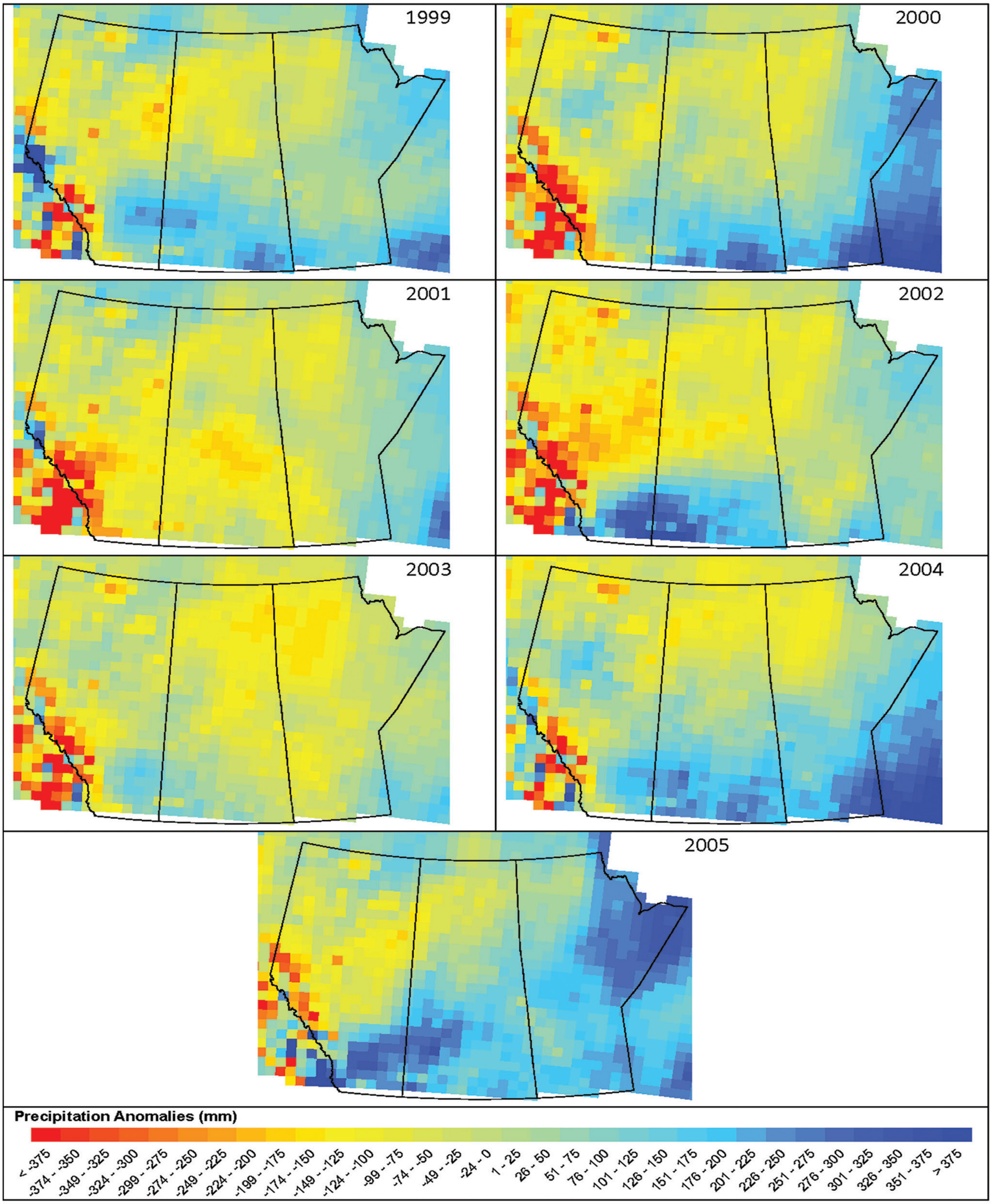


**Figure 1**. Annual mean precipitation departures from normal (millimetres; based upon the 1971-2000 mean) in millimetres for 1999-2005. Blue/purple colours represent above-normal precipitation, while yellow/red colours denote below-normal precipitation. Numerous low precipitation records were broken during the drought.

past. Possible large-scale atmospheric reasons for this are highlighted in articles by Bonsal and Shabbar (this volume), and are only briefly discussed here.

Climate teleconnections such as El Niño are large-scale semi-persistent global and regional oceanic and atmospheric features that can be indicative (and even allow seasonal predictions) of how atmospheric wind, temperature, and precipitation behave over different regions of the globe (e.g., Shabbar and Khandekar, 1996; Bonsal et al., 2001). In the first period of the 1999-2005 drought, a moderate to strong La Niña occurred between 1999-2002 and then switched to weak El Niño conditions in 2003-2004. The Pacific Decadal Oscillation (PDO) and Pacific North American (PNA) patterns were predominantly negative during the most extreme part of the drought (2001 and 2002) and positive thereafter, while the Atlantic Multi-Decadal Oscillation (AMO) was in a positive phase throughout the entire period. The lack of both a consistent positive PNA pattern (indicative of high-pressure drier systems over Western Canada) and a persistent positive PDO during the most extreme drought conditions in 2001 and 2002 differs from the large-scale teleconnections associated with previous extended dry periods on the Canadian Prairies (e.g., 1961 and 1988). The mid-tropospheric atmospheric circulation patterns during 2001 and 2002 lacked the distinct meridional flow (larger amplitude wave pattern) over the North Pacific and North America that normally characterizes drought in Western Canada. When examining these large-scale atmospheric flows in greater detail, as an example from May 2001, an anomalously strong westerly upper jet stream from the Pacific produced strong descent in the lee of the Rocky Mountains (called downsloping) and associated drying over the Prairies (J. Gyakum, personal communication; not shown). During May 2002, storm tracks were shifted to the south and east of the Prairies, with cold air transport associated with subsidence and drying associated with large-scale weather system passages. Hence, a drought can be driven by very different large-scale conditions, with no particular association with temperature departures from normal. Similar processes are at play for other such poleward moisture transport conditions (e.g., Roberge et al., 2009). The key processes involved are those that drive subsidence. There are many such meteorological processes, with only two being identified here.

It is common to have less cloud cover during drought than other non-drought periods. It was found, however, that the 1999-2005 drought had more cloud than previous droughts dating back as far as 1984 (see Leighton, this volume, for more detail). Many regions experienced below-normal cloud between 1% and 6%, while regions in western and northern Alberta had more cloud than normal (up to 6%) during the 1999-2003 period. Once again, this may have been at least partially due to the different large-scale atmospheric flow patterns discussed above. More research is needed to investigate the driving factors of major large-scale drought pattern differences and their associations with precipitation, temperature, and cloud cover.

In terms of more extreme weather characteristics during the drought, of such a significant rain event – with 10 mm or more – nearly 80% were solely or partially convective (i.e., lightning was recorded during the event), while more than 85% of the total rain area was from events with thunderstorm activity (Raddatz and Hanesiak, 2008). This highlights the importance of thunderstorm processes and associated rainfall on the Prairies. By 2004, much of the Prairies had no longer suffered drought conditions, mainly due to more large-scale weather system occurrences. It was found, however, that there was no clear-cut relation between a lack of precipitation and the lack of summer cold low (a special type of low-pressure weather system) occurrences in Alberta and Saskatchewan during the 1999-2003 period; sometimes there appeared to be linkages but in some cases there were none. Cold lows in summer are notorious for bringing extended periods (days) of cool, wet weather and, in some cases, extreme rain events. More detailed analysis is needed to investigate whether the source region, moisture supply, and speed of these cold lows are important considerations over a longer time period of study.

The annual average number of hail and tornado occurrences (days) on the Prairies are 254 ± 129 (86.5 ± 25 days) and 46 ± 17 (28.7 ± 8 days), respectively, relative to the 1985-2007 period. It was found that there were many fewer hail and tornado days and occurrences than normal (between 30% and 69% of normal) over the drought period of interest, particularly between 2000 and 2002, with some years being the second- and third-lowest over the 1985-2007 period. The years 2004 and 2005 were wetter years and had near-normal tornado and hail occurrences and days. More analysis is needed to see whether this is typical of other major droughts of the past. The hail and tornado results here, however, are consistent with Hanesiak et al. (2009), who found that there was some predictive capability when using crop-modelled soil moisture to determine whether one could expect less-than-normal subsequent occurrences and days of large hail and tornadoes for dry areas as opposed to wet areas.

Thunderstorms and associated lightning activity are a common occurrence over the Canadian Prairies. A comparison of lightning activity during the early and mid-drought (1999-2003) and the late and post-drought (2004-2008) periods over the grassland, boreal, sub-arctic, and southern cordilleran eco-climatic zones was performed. The lightning data used are from the Canadian Lightning Detection Network (CLDN; Burrows et al., 2002). Results showed that lightning activity was more variable during the early and mid-drought period than during the late and post-drought period over the boreal and grasslands ecozones. Slight negative (positive) trends during the drought (post-drought) periods are noted over both ecozones. In contrast, lightning activity over the cordilleran and arctic ecozones exhibited little variation when comparing the drought and post-drought period. There were generally slightly more lightning days in the grasslands than in the boreal forest during the drought period, but this pattern was not evident during the post-drought period. The fewest lightning days in the boreal, grassland, and cordilleran ecozones occurred in 2002 during the drought period, a year when the drought reached its maximum spatial extent. The polarity of cloud-to-ground (CG) lightning discharges can be classified either as negative or positive. A number of studies have reported that high fractions of positive CG lightning are usually associated with severe weather (e.g., Carey and Rutledge, 2003). There appears to be a difference in positive CG lightning activity between the drought and post-drought periods. The drought period had fewer positive CG flashes than the post-drought period, suggesting that fewer severe storms may have occurred during the drought. This is consistent with the observations that hail and tornado occurrences during the drought were much below normal.

Looking at the lightning and land surface data in a more detailed manner revealed a significant correlation between the land surface and atmospheric conditions. A novel study designed to explore linkages between the Normalized Difference Vegetation Index (NDVI; see more on NDVI in the forthcoming section) and CG lightning duration (DUR, from the Canadian Lightning Detection Network) was undertaken for ten summers between 1999 and 2008 on the Canadian Prairies (Brimelow et al., 2010a). The study showed that summertime lightning activity is overwhelmingly below average within larger “dry areas” (i.e., areas with below-average NDVI); that is, the linkages between NDVI and DUR increased significantly as both the area and magnitude of the dry anomaly increased. In contrast, areas with above-average NDVI did not consistently experience above-average lightning activity, regardless of the area size. In addition, the lower threshold for the area of the dry anomalies to have significant correlation to reduced lightning activity was found to be approximately a diameter of 150 km. The correlation increased as the size of the dry area increased. Thus, the surface-convection feedback may be a real phenomenon, in which drought tends to perpetuate drought with respect to convective storms and associated rainfall. More research is needed to assess cause and effect (i.e., what proportion of the lack of storms is due to dry soils compared to other factors that initiate and perpetuate storms?).

During the cold season, the 1999-2005 period had on average more days with temperatures greater than 0°C, fewer hours of blowing snow, and more freeze-thaw days compared to the 1965-2006 period. In addition, between 1999-2005, 36 extreme precipitation events occurred at several selected observation stations with a maximum severity of 291% of the monthly average (i.e., daily precipitation recorded was almost three times the average monthly precipitation). Twelve of these events consisted of record-breaking accumulated daily precipitation. It was also found that over the historical record (as far back as 1960), the incidence of extreme precipitation events during drought increases as the severity of the event increases, particularly for larger extreme events (i.e., daily precipitation greater than 150% of the monthly average precipitation). This suggests that extreme longer-term events such as drought may affect the severity of shorter-term weather events with possible linkages to close proximity wet/dry areas.

## Surface Characteristics

This section focuses on characterizing the spatial and temporal variations of the surface (surface to root zones), including vegetation (and common drought indices) and surface hydrology during the 1999-2005 period. It will also contain more historic data where possible in order to provide a broader perspective.

The 1999-2005 drought progressed roughly from west to east across the Prairies and appeared to be linked to drought that was occurring in the United States simultaneously, as shown by various datasets (e.g., precipitation from the previous section, modelled soil moisture, NDVI, Palmer Drought Severity Index (PDSI), and Standardized Precipitation Index (SPI)). Not all of these data will be shown, since they were all relatively consistent in depicting the overall large-scale drought pattern in each year. As an example, however, NDVI anomalies (departure from normal) for mid-July of each year are shown in Figure 2 for 2000 to 2005. NDVI is based on satellite imagery and is commonly used to identify areas of stressed vegetation over regional scales (e.g., Wan et al., 2004). The blue colours in Figure 2 indicate below-normal NDVI (greater vegetation stress), while yellow/red colours indicate above-normal NDVI (little to no vegetation stress). In 2000, stressed vegetation was primarily seen in southern Alberta. It greatly expanded to a larger area by 2001 and

2002. Southern regions of Alberta and south-west Saskatchewan received some relief from the drought (shown by above-normal NDVI) by mid-July in 2002, primarily due to only two major large-scale weather systems that produced widespread rain and even heavy rain in some areas prior to mid-July (see Figure 1). By 2003, enhanced drought was primarily confined to southern Saskatchewan and south-west Manitoba, although other regions showed below-normal NDVI as well. By 2004, much of the original drought area was no longer experiencing drought. The below-normal NDVI values in southern Saskatchewan in 2004 and in southern Manitoba in 2005 were primarily due to too much water.

Snow cover, snow depth, and satellite-derived snow-water equivalent were generally less than normal over the southern Prairies during the drought. This pattern is consistent with below-normal winter atmospheric moisture transport over the Prairies from the Pacific Ocean and very little convergence (i.e., piling up) of moisture over the region. Both snow cover extent and snow-water equivalent can be estimated using satellite imagery (e.g., Goodison and Walker, 1995; Derksen et al., 2003), and snow depth is determined from observational analysis (Brown et al., 2003). The reduced snow cover in spring contributed to soil moisture deficits during 2001 and 2002, which in turn were linked to the reduced evapotranspiration (ET) during

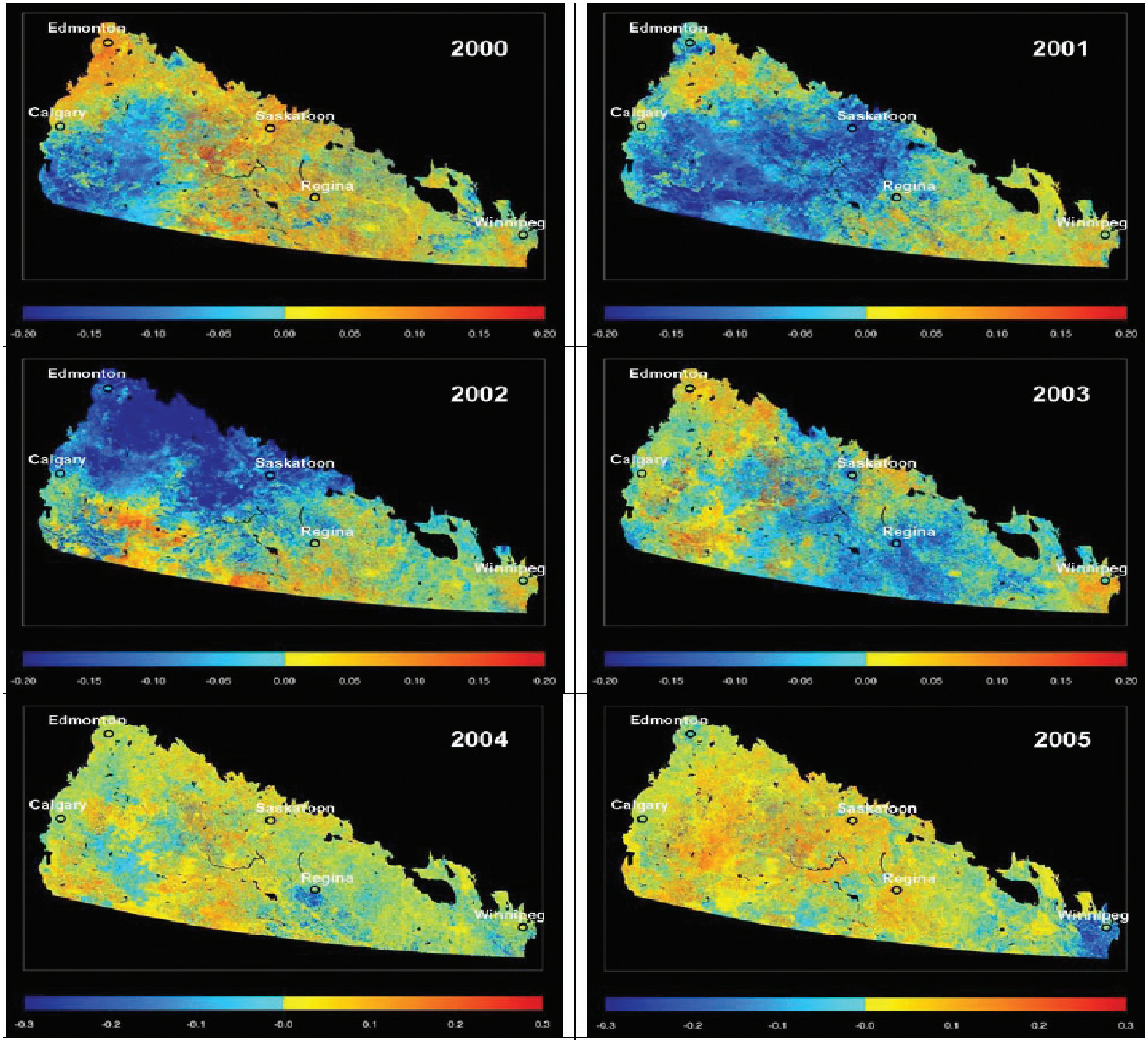


**Figure 2**. The NDVI departures from normal between 2000 and 2005, based on the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite. The maps represent a ten-day period between July 11 and July 20.

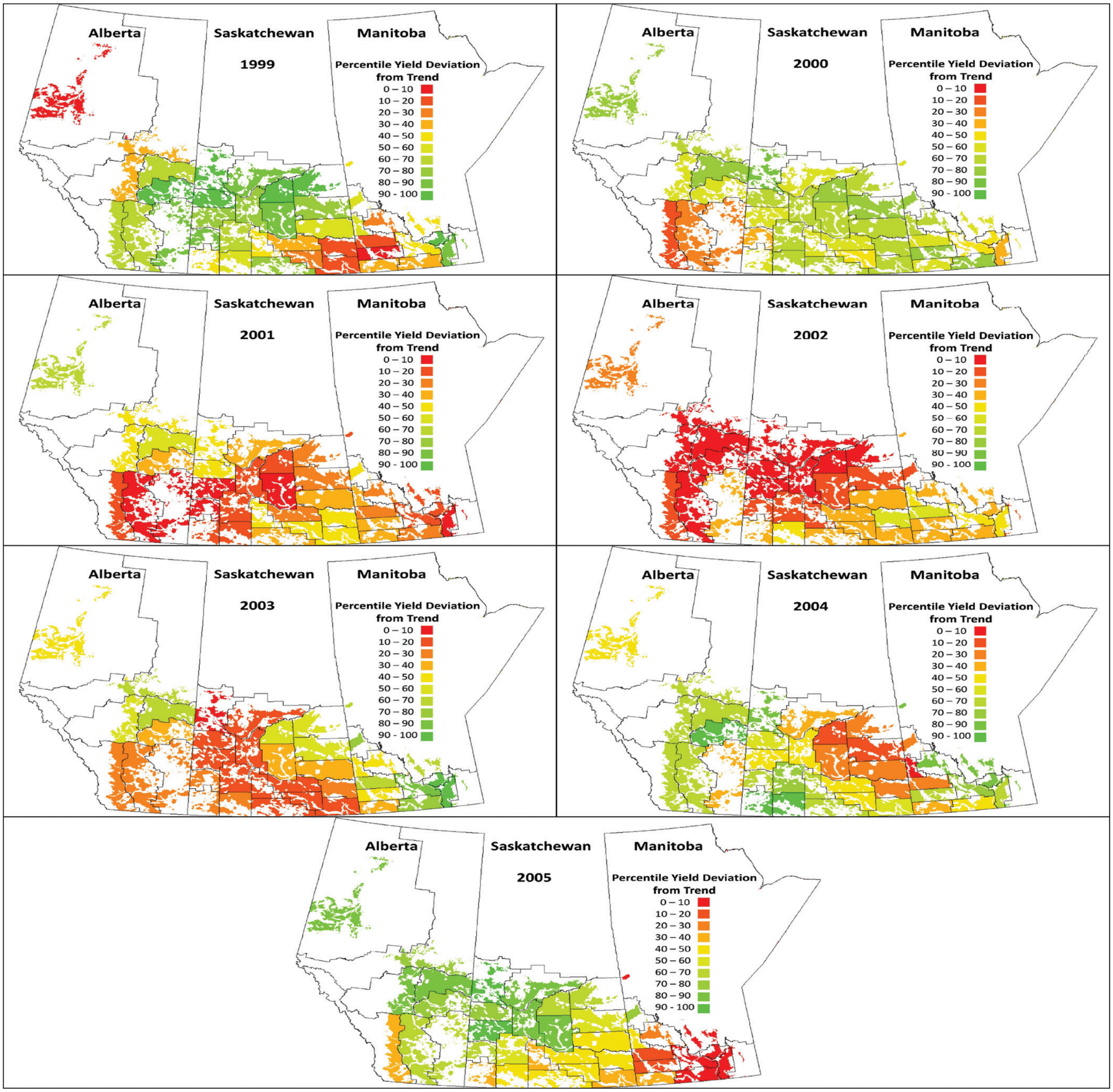


**Figure 3.** Percentile yield deviation from trend by Census Agricultural Region (CAR) in Western Canada for 1999-2005. Values for each CAR are the area-weighted means for yield deviation from trend for spring wheat, barley, canola, and field peas.

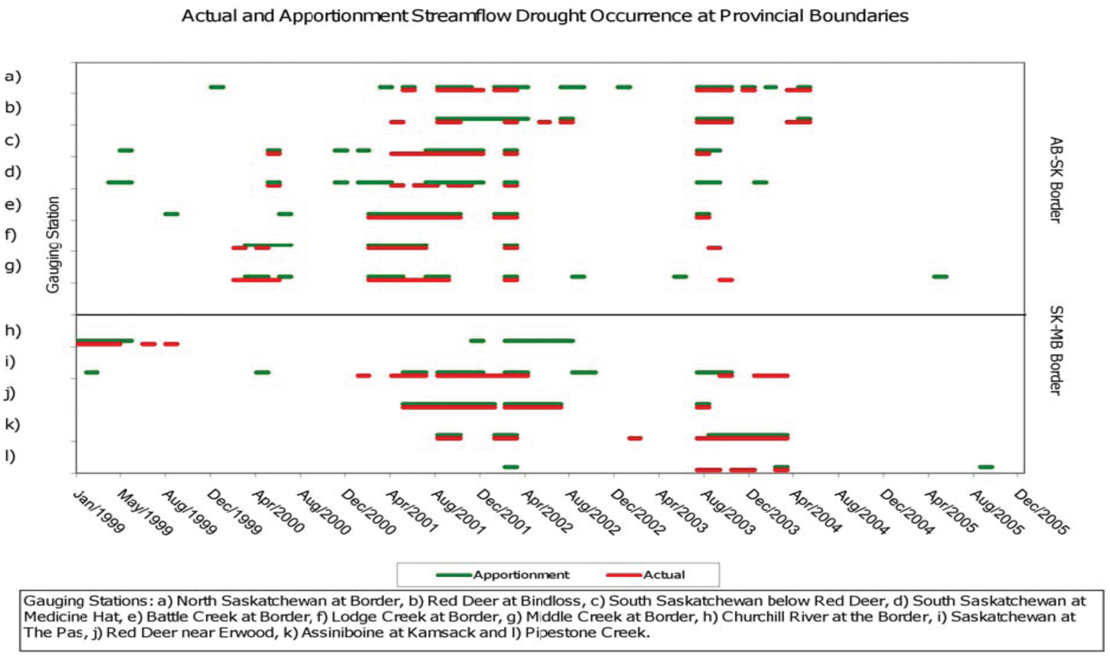
the growing season (Szeto, 2007). The previous autumn's precipitation can be critical for the coming spring and summer because it recharges soil water storage. Reduced precipitation in autumn can lead to drier soils in spring and, if the following spring is very dry, this will further enhance moisture stress for the growing season. Since the Prairies have a significant number of streams and small watersheds that do not always flow into major rivers draining out of the Prairies (called non-contributing hydrological areas), winter can also play a role in spring/summer water stress, with less snow cover to recharge the soil moisture during the spring melt period, as was experienced in 2001-2002. By the winter of 2003 to 2004, snow depths were near normal for much of the Prairies that had experienced drought.

Crop yields were significantly affected during the 1999-2005 period, based on Statistics Canada data (Statistics Canada, 2009; Figure 3). Low crop yields in Manitoba and Saskatchewan were caused by flooding rather than drought in 1999; however, drought effects became apparent in southern Alberta by 2000. From 2001 through 2003, yields were greatly depressed, with the lowest values on record for many areas occurring in 2002 and a few record low yields in 2001 and 2003. By 2004 and again in 2005, yields had generally recovered across the majority of the Prairies with below-normal yields being primarily due to wetter-than-normal conditions. The results are consistent with other crop yield analyses during the drought period (Wittrock, 2005).

In contrast to most croplands, forests tend to respond slowly (over periods of one or more years) to moisture deficits during periods of drought (e.g., Krishnan et al., 2006). Severe impacts on forests took place 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 (more detail about boreal forest impacts can be found in articles by Hogg and Amiro, this volume). Climate Moisture Index (CMI) values indicated conditions that were the driest ever recorded in over 100 years in this area. The CMI has been used to assess drought impacts on forest distribution, growth, and dieback in the past (e.g., Hogg et al., 2008). 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% to 40%) decreases in annual evapotranspiration and gross ecosystem photosynthesis, which were associated with a parallel decrease in aspen leaf area (Krishnan et al., 2006; Barr et al., 2007). The effects of drought can vary markedly depending on the type of tree and soil conditions.

The grasslands in southern Alberta had their lowest ET in 2001 following two years of below-average precipitation, which contributed to plant water growth stress (Flanagan, 2009). ET recovered in 2002, however, with increased precipitation during spring, and then remained relatively high in subsequent years. This was indicative of improved grass growth. The above-average precipitation events in 2002 and 2005 occurred during the growing season, which not only helped increase ET in the year received but carried over water into subsequent years (Flanagan, 2009). More details illustrating the drought effects on the boreal forests and grasslands can be found in other sections of this publication.

Hydrological droughts are important because their consequences for water availability affect all aspects of the economy and society. They are visible reminders that very dry conditions continue to prevail. Hydrological drought is more difficult to characterize than other types of drought because measurements at a hydrometric station reflect meteorological and hydrological processes that have been taking place over large upstream areas and longer time periods to generate flow at the station. The effects of the 1999-2005 drought on flows across the borders between the affected Prairie Provinces (Alberta, Saskatchewan, and Manitoba) were studied using actual flow data from Environment Canada and naturalized flows computed by the Prairie Provinces Water Board for use in administering interprovincial agreements. Naturalized flow values provide estimates of the flow that would occur if there had been no human interventions such as dams, reservoirs, drainage, and land use changes. A threshold analysis



Gauging Stations: a) North Saskatchewan at Border, b) Red Deer at Bindloss, c) South Saskatchewan below Red Deer, d) South Saskatchewan at Medicine Hat, e) Battle Creek at Border, f) Lodge Creek at Border, g) Middle Creek at Border, h) Churchill River at the Border, i) Saskatchewan at The Pas, j) Red Deer near Erwood, k) Assiniboine at Kamsack and l) Pipestone Creek.

**Figure 4.** The distribution of very low streamflows (<Q10) during 1999-2005 on the Canadian Prairies.

was used to define and study periods when flows below a certain threshold occurred. In this case, the calculated monthly low flow that occurred less than 10% of the time (Q10) was selected as the threshold.

Figure 4 shows the times when the actual and naturalized flows were below the threshold during 1999-2005. For the Alberta-Saskatchewan stations (in the upper part of Figure 4), the low flows dominated between March 2001 and April 2002. Low flows appeared again in the summer of 2003 but they did not persist as long. During the earlier period of very low flows, the flows along the Manitoba-Saskatchewan border lagged the low flows on the Alberta-Saskatchewan border, suggesting that the low flow anomalies may have propagated downstream or the drought and its associated below-average precipitation anomalies may have propagated from west to east (in the same direction). This is consistent with other analysis of, for example, precipitation and NDVI maps shown previously. In 2003 the low flows occurred more simultaneously along the two borders.

Based on the analysis of these flows, the following conclusions can be reached: 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 occur at specific stations. It is important that those who make decisions based on naturalized flows be aware of these differences, particularly 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 that can last for more than one month (not shown here).

In terms of drought itself, the picture that emerges from this analysis is that although some basins were dry in southern Alberta, these were small tributaries that are frequently dry in summer. In 2001 and 2002 in particular, the flows in northern and southern Saskatchewan were below the Q10 value and 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. Beyond the spring of 2004, most flows were above the Q10 thresholds.

Closed-basin lakes can be extremely sensitive to drought and overall climatic variability, primarily because the Prairies have a large non-contributing hydrologic area (e.g., van der Kamp et al., 2008). Water level changes in these lakes can indicate the dynamic balance between runoff, precipitation, and evaporation and can improve our understanding and prediction of the local hydrology during drought. Lake levels are also influenced by changes in land use, drainage, groundwater variations, and other water management infrastructure such as dugouts. There is an overall pattern throughout most of the twentieth century of declining lake levels, with some exceptions (van der Kamp et al., 2008). During the largest year-to-year declines of lake water levels, declines can range between 200 mm and 600 mm and occur in years with little or no runoff to the lakes, low precipitation, and strong evaporation. These conditions occurred during the 2000-2003 period and during other notable drought periods. In addition, the upward and downward trends in lake levels appear to be consistent with wet and dry periods, respectively, determined through drought indices time series (Bonsal and Regier, 2007; van der Kamp et al., 2008). Stream runoff in the Prairie region has indicated a declining trend (Zhang et al., 2001), which is also consistent with the decline in lake levels, especially in dry years (van der Kamp et al., 2008). Greater detail can be found in the article by van der Kamp and Hayashi (this volume).

Wetlands were also severely affected by the drought, with most shallow wetland basins drying out entirely. In 2002, the number of ponds holding water declined to the lowest level since counts started in 1961, although at a level comparable to the minimums that occurred in 1989 and 1981. As described by van der Kamp and Hayashi (this volume), the number of wetlands holding water is very sensitive to snow accumulation during the preceding winter because most of the smaller basins dry out by the end of each summer and refill with snow-melt, as mentioned earlier.

## Sub-surface Characteristics

Groundwater is a critical source of water for drinking and agricultural use for many rural communities. Water level changes in shallow wells reflect variations of annual recharge, which occurs mostly in springtime, and is therefore largely controlled by snow-melt infiltration. During the drought, the water levels in surficial aquifers declined by about 0.5 m on average over several years, with the lowest levels generally occurring in the winters of 2003 and 2004 (see van der Kamp and Hayashi, this volume, for more detail). Water levels in most wells rose back to normal within two or three years following the cessation of drought, showing that groundwater reacts slowly to drought conditions and that water table changes rarely amount to more than 1 m. Such small water level changes only affect the yields of very shallow wells with already low yields.

Characterization of drought beneath the surface can be difficult over large areas and is possible if available stored moisture in the soil can be measured or estimated. Unfortunately, the estimation of this storage via watershed modelling can be challenging and sometimes yields wrong estimates. Direct estimation of integrated watershed storage via the Gravity Recovery and Climate Experiment (GRACE) remote sensing satellite mission could serve as a surrogate for the deficiencies arising from the determination of this storage from traditional watershed modelling. The GRACE-based total water storage measurements were used in the computation of the Total Storage Deficit Index for the 2002-2006 period in the Saskatchewan River Basin (SRB; see Yirdaw et al., 2008; Figure 5). Negative average terrestrial water storage anomalies over the entire SRB commenced in the summer of 2002 and continued into the spring of 2004. Unfortunately, no GRACE measurements are available prior to 2002; it is impossible to illustrate time lags between the beginning of total water storage deficits and precipitation deficits shown in the "Atmospheric Characterization" section.

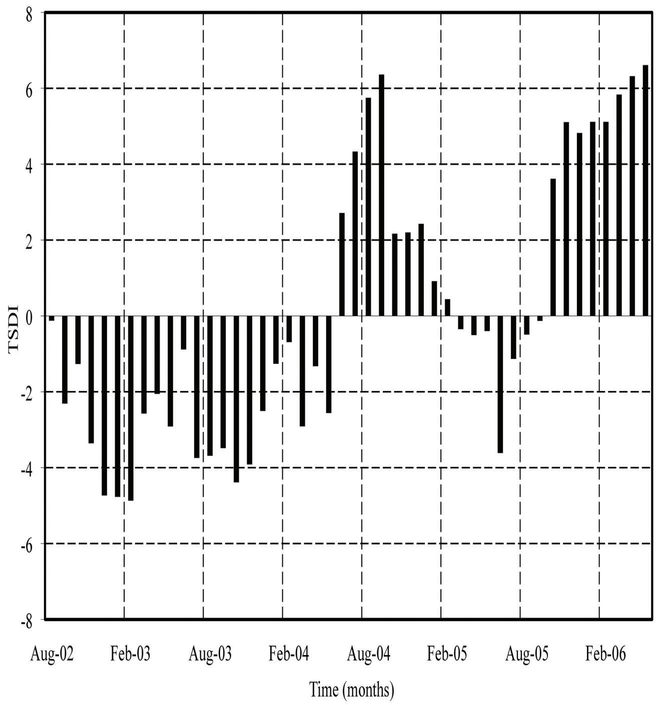


**Figure 5**. Total Storage Deficit Index estimated from the GRACE-based total water storage anomalies for the Saskatchewan River Basin.

## Implications

It is encouraging that many of the datasets and model products used by DRI were consistent with locating the major drought areas, although there were some differences when comparing the finer scale features such as the location of the transition regions between the very dry and wet regions. This was mainly due to the differences in spatial resolution between the various products and what the data source (or product) was meant for, or capable of resolving. In addition, although drought indices such as the SPI and PDSI are commonly used to monitor drought, crop and hydrologic models that predict soil moisture content and runoff potential as well as NDVI vegetation state have improved to the degree that they may be used to assess these factors explicitly. A combination of products can be used to investigate various types of drought to assess the overall potential real-time impacts of a drought, depending on the application desired. For example, assessing the "real-time" spatial extent and severity of an agricultural drought may be accomplished by assessing a combination of products to ensure they paint the same picture, such as using weekly composite MODIS-derived NDVI anomalies in combination with daily crop model (e.g., PAMII; Raddatz, 1993) soil moisture/crop stage information and the Variable Infiltration Capacity (VIC) model soil moisture (see Lin and Wen, this volume, for VIC applications). When NDVI anomalies approach -1.0, they correspond well with observed and modelled (from PAMII) plant available water of the order of 30%, when crops begin to show significant stress levels (Brimelow et al., 2010b). With MODIS NDVI imagery resolution at 250 m, high spatial resolution data can be valuable down to the farm level. For surface hydrologic applications, gauged stations can indicate significant drought once actual stream flows are within or less than the 10% percentile of normal. Different thresholds can be used depending on how one defines drought. For surface and sub-surface hydrology, the GRACE satellite shows promise for monitoring the Total Storage Deficit (TSD) over large basins and downscaling to smaller basins if required. GRACE-derived TSD can be used in conjunction with atmospheric re-analysis products or numerical weather prediction model analyses to monitor both TSD and atmospheric water balance-derived storage deficits for comparisons. These are only some examples. Other products that have been highlighted in this article can also be used in many other ways to improve drought monitoring.

*Overviews*

# WHAT EFFECTS DO DROUGHTS HAVE IN CANADA? HIGHLIGHTS OF THE REPERCUSSIONS OF A MAJOR MULTI-YEAR DROUGHT

*Elaine Wheaton*

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## Introduction and Motivation

Drought is one of the world's and Canada's most significant natural hazards. Droughts have major impacts on the economy, environment, health, and society. Droughts were responsible for seven of the ten most costly natural hazards in Canada, with damages ranging up to almost $6 billion (Etkin et al., 2005). A critical goal for society is to explore the characteristics of droughts, including their impacts. Knowledge of their impacts forms the basis for determining effective ways to avoid or reduce damages.

The most recent severe drought in Canada occurred from 2001 to 2002. This article highlights the 2001 and 2002 drought in Canada in order to set directions to learn more about decreasing or avoiding negative impacts. The drought of 2001 and 2002 in Canada covered massive areas, was long-lasting, and brought conditions unseen for at least one hundred years in some regions. For example, western Saskatchewan was drier in 2001 than in any year of the 1930s dust bowl; Saskatoon was 30% drier in 2001 than in any other year in the past 110 years (Wheaton et al., 2008).

The years 2001 and 2002 likely brought the first coast-to-coast drought on record. This drought also appeared to cover more areas of Canada compared to previous infamous droughts of 1931, 1961, and 1988. It was a rare event in that it affected areas less accustomed to dealing with droughts. These areas included parts of eastern Canada and the northern agricultural Prairies. Drought impacts were concentrated in the West: Saskatchewan and Alberta were the hardest hit (Wheaton et al., 2008).

This article provides an overview of the effects of the 2001-2002 drought with emphasis on agriculture, water, and the economy. A set of lessons learned from the drought is provided, followed by the major conclusions. These types of assessments of drought impacts are rarely done and are needed. This article is meant to reinforce the reasons for drought research described in other parts of this article.

## Data and Methodology

This article is an overview of the first national assessment of drought impacts in Canada based on a biophysical and economic assessment of the 2001-2002 drought completed by Wheaton et al. (2005, 2008). Many agencies cooperated to support this project and subsequent deliverables. Cooperation of this scale is vital for the success of such an assessment.

Drought can affect many sectors and this means that various types of data from many sources are required for impacts and adaptation assessments. Our assessment drew on several data types including climatic, hydrologic, and economic data. Secondary sources of data included public and semi-public sources. The print media was especially useful to determine leads for impacts to consider and for information about adaptations.

Primary data sources included phone interviews, focus groups, print media surveys, and economic modelling. The data and research framework are discussed in further detail in Wheaton et al. (2008). The cause-effect research framework applied included relationships among drought causes, drought characteristics, physical, biological, and economic impacts, and adaptations.

## Results and Discussion

In general, droughts in Canada affect only one or two regions, are relatively short-lived (one or two seasons), and affect only a few sectors of the economy. In contrast, severe droughts that cover large areas and are multi-year affect most sectors of the economy. The drought years of 2001 and 2002 had a devastating impact on many economic sectors. Agricultural production dropped an estimated $3.6 billion for the 2001 and 2002 drought years, with the largest loss (at more than $2 billion) occurring in 2002. Nationally, the GDP fell some $5.8 billion for 2001 and 2002, again with the largest loss taking place in 2002, at more than $3.6 billion. Employment losses exceeded 41,000 jobs, including nearly 24,000 jobs in 2002. Net farm income was negative or at zero for several provinces for the first time in 25 years. A negative net farm income occurred in Prince Edward Island for 2001 and in Saskatchewan for 2002, and a zero net farm income was reported in Alberta for 2002. Crop production losses were devastating for a wide variety of crops across Canada, particularly in 2001. Livestock production was especially difficult due to the scarcity of feed and water. Some livestock inventories decreased, especially in Alberta. Previously reliable water supplies were negatively affected and several failed. Water supplies considered included surface water such as streams, wetlands, dugouts, reservoirs, and groundwater.

Unlike many previous droughts, which affected one or relatively few economic sectors, multi-sector effects were associated with the 2001 and 2002 droughts. Both drought years affected areas as wide-ranging as agricultural production and processing, water supplies, recreation, tourism, health, hydroelectric production, transportation, and forestry. Long-lasting impacts included soil and other damage by wind erosion, deterioration of grasslands, and herd reductions. Some of these systems take decades or longer to recover.

Several government response and safety net programmes partially offset the negative socio-economic impacts of the 2001 and 2002 drought years. Given the unprecedented nature of both drought periods, however, the response from all sectors could not be expected to completely address the problems. Crop insurance payments were very high in 2001 and 2002, especially in Saskatchewan and Alberta. Saskatchewan saw a large increase in payments, from $331 million in 2001 to $1.1 billion in 2002. Alberta's crop insurance payments jumped from $274 million in 2001 to $790 million in 2002.

## Lessons for Enhanced Drought Adaptations

The 2001 and 2002 droughts would have likely been much worse without the experience gained from preparing for and coping with previous droughts. Several adaptation measures were suggested and used, but many were costly and disruptive. Many adaptations proved insufficient to deal with such an intense large-area and persistent drought, underlining Canada's vulnerability to such events. Adaptation research, including audits and testing, requires considerable enhancements. Drought causal factors are not well understood. The large-area atmospheric and oceanic patterns suspected to have caused previous major droughts were distinctly different than those associated with this more recent drought. This suggests that a better understanding of causal factors is needed to reduce our vulnerability by providing early warning and more lead time for adaptations. The risks of drought are greater than previously thought. Evidence indicates that droughts may become worse as a result of climate change, requiring a far greater adaptive capacity. Current adaptive capacity may be high (Sauchyn and Kulshreshtha, 2008), but we need to boost it to deal with future droughts, which will be worsened by climate change and other factors.

## Conclusion

The 2001 and 2002 drought was exceptional by many measures and extremely important to examine because it was unusually large, severe, and embedded in a long dry period. The drought was associated with devastating impacts and required significant costly, disruptive, and problematic adaptations. Even with considerable work to adapt to the drought, residual short- and longer-term impacts resisted adaptation and provided lessons that can be used to reduce the risk of losses to future droughts.

## Acknowledgements

Thanks to the Prairie Farm Rehabilitation Administration (now Agri-Environment Services Branch), which originated the work with guidance from Agriculture and Agri-Food Canada's Canadian Drought Committee and Review Teams. The Project Team included: Elaine Wheaton and Virginia Wittrock (SRC); Suren Kulshreshtha (University of Saskatchewan); Barrie Bonsal and Grace Koshida (Environment Canada); Charles Grant (University of Manitoba); and Phil Adkins, Aston Chipanshi, Gord Bell, Allan Howard, Bob MacGregor, and George Brown (AAFC). This overview was supported by Environment Canada (Adaptation and Impacts Research Division) and by DRI. Thanks to Richard Lawford for many helpful suggestions.

*Atmospheric Sciences*

# LARGE-SCALE ATMOSPHERIC CIRCULATION PATTERNS AND SEVERE DROUGHTS ON THE CANADIAN PRAIRIES

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## Why the Research was Undertaken

It is a well-known fact that prolonged, large-area droughts are among Canada's costliest natural disasters. They have major impacts on a wide range of sectors, including agriculture, forestry, industry, municipalities, recreation, health and society, and aquatic ecosystems. Although most areas of Canada experience drought, southern regions of the Canadian Prairies are most susceptible. In fact, at least 40 major droughts have occurred on the Prairies over the past two centuries, with multi-year episodes observed in the 1890s, 1930s, 1980s, and the most recent 1999-2005 episode. Even though considerable research has been undetaken on the subject of droughts, scientists still do not fully understand why they form, persist, and eventually end. We do know, however, that droughts are caused by a severe lack of precipitation, which is often worsened by extreme high temperatures that increase evaporation and transpiration. Past research (prior to the 1999-2005 Prairie drought) has shown that the major factor that leads to these hot, dry conditions involves distinct patterns in upper-atmospheric circulation or the jet stream. Over the southern Canadian Prairies, summer droughts have been associated with a distinctive atmospheric circulation pattern that includes a large-amplitude ridge centred across the area (see Figure 1) that often persists for several weeks. This pattern effectively blocks storms from entering the Prairie region. The shape of the ridge in Figure 1 is similar to the Greek letter Omega; thus this atmospheric circulation pattern is often referred to as "Omega Blocking." The ridge pattern also causes descending air currents, which results in high surface temperatures.

Note that droughts are not always just a summer occurrence, since they can be initiated and/or accentuated during the winter season. The lack of snowfall results in lower-than-normal spring runoff, leading to reduced stream flow and reservoir and soil moisture replenishment. Winter droughts are also affected by a persistent atmospheric circulation pattern similar but not identical to the one shown in Figure 1. This winter pattern not only diverts storms from the Prairie region, but also allows warm air from the south to enter the Prairies, causing sublimation of the snow pack.

Reasons for the initiation and persistence of the atmospheric circulation patterns that lead to drought are not entirely understood, but are likely influenced by variations in Pacific Sea Surface Temperatures (SSTs). These SSTs, which cover a very large area, directly affect local to regional atmospheric circulation patterns that, in turn, can change large-scale atmospheric circulation over other areas of the globe. This process has been termed a "teleconnection". In fact, past research has identified relationships between these teleconnections and temperature and precipitation patterns over North America, including the Canadian Prairies. The most common and well-known relationship for the Prairies occurs between the El Niño (see www.smc-msc.ec.gc.ca/education/elnino/index_e.cfm) and La

Niña (see www.smc-msc.ec.gc.ca/education/lanina/index_e.cfm) events and winter/spring temperature and precipitation. In general, El Niño (warmer-than-normal SSTs in the eastern tropical Pacific Ocean) produces an atmospheric circulation pattern that causes warmer/drier Prairie winters, while La Niña (colder-than-normal SSTs in the eastern tropical Pacific Ocean) has an opposite effect. El Niño and La Niña events occur on average every two to seven years. Linkages between Prairie temperatures and precipitation and variations in North Pacific SSTs are also evident, but mainly during the winter season. Some studies have shown that a North Pacific SST pattern that includes colder-than-normal water in the central North Pacific and warmer-than-normal temperatures along the west coast of North America (called a positive Pacific Decadal Oscillation, or PDO) can cause atmospheric circulation patterns that lead to extended summer dry periods over the Canadian Prairies.

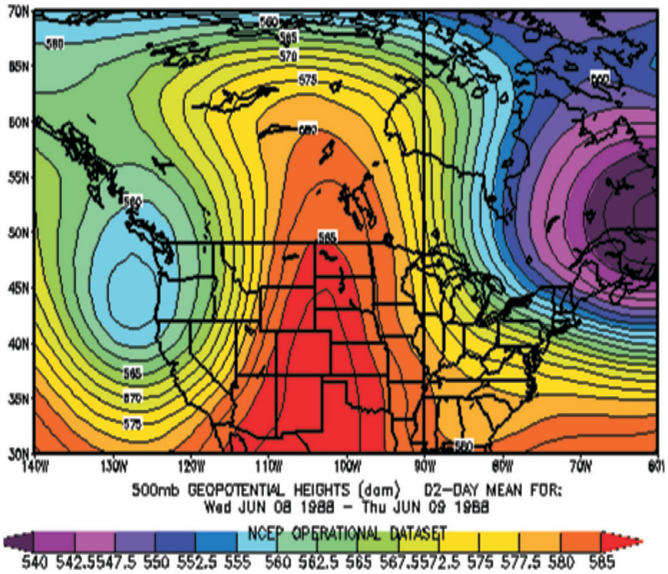


**Figure 1.** Typical "Omega Blocking" atmospheric circulation pattern over the Prairie region of North America (June 8, 1988).

Even though previous studies have examined the atmospheric patterns and teleconnections associated with droughts over the Canadian Prairies, none have specifically focused on those that occured during the 1999-2005 episode. The main objective of this research is to assess the similarities and differences of the atmospheric circulation and teleconnections of the recent drought (focusing on the years 2001 and 2002, which were the most severe drought years in the 1999-2005 period) to those that occurred during the severe multi-season Prairie droughts of 1961 and 1988. The results will help determine if the atmospheric causes of the 1999-2005 drought were consistent with previous extreme dry episodes on the Prairies.

## The Research Undertaken

The main objective of this research is to compare the 2001-2002 upper-atmospheric (at the 500 hPa level of the atmosphere) circulation patterns and teleconnections to those associated with historical, multi-season droughts over the Canadian Prairies. Although several previous Prairie droughts have been documented, the most severe in terms of persistence and impacts include the multi-year droughts of the 1930s and 1980s (with 1988 being the worst drought year), and 1961, which is considered the most extensive single-year Prairie drought of the twentieth century. Upper atmospheric data are not available prior to 1946, which precludes examination of the 1930s drought. Since all of these major droughts were initiated during the previous autumn, comparisons of the 2001 and 2002 atmospheric circulation patterns to those of 1961 and 1988 are conducted for the autumn to summer period (September 1960 to August 1961 for the 1961 drought). This coincides with the multi-season dry period associated with all four drought years and also represents the traditional agricultural year on the Canadian Prairies.

## Summary of the Findings and their Importance

The main finding from this research was that although the major droughts of 1961, 1988, and 2001-2002 were similar in terms of their lack of precipitation and spatial coverage over the Prairies (see Figure 2), the atmospheric circulation and teleconnections during the most recent episode were somewhat different from the 1961 and 1988 events. In particular, Figure 3 shows that the atmospheric circulation during 1961 and 1988 was characterized by a persistent ridge over western and central Canada, as evidenced by the stronger positive anomalies (red colours) over the area. These circulation patterns are very similar to those shown in Figure 1. The atmospheric circulation during 2001 and 2002 in Figure 3 show distinct differences compared to 1961 and 1988. In both 2001 and 2002, positive anomalies were situated over much of the North Pacific and North America. In 2002, however, they were mainly confined to the United States and parts of southern Canada. This dissimilarity is clearly evident in Figure 4a, which shows the difference in atmospheric circulation between the 1961 and 1988 droughts and the average for the 2001 and 2002 droughts (1961/1988 minus 2001/2002).

The positive differences over Western Canada, including the Canadian Prairies, illustrate a more ridge-like pattern (similar to Figure 1) during 1961 and 1988. This is even more apparent during the summer season of June, July, and August (Figure 4b). During the summer season, this ridging atmospheric circulation pattern causes descending air currents, which results in high

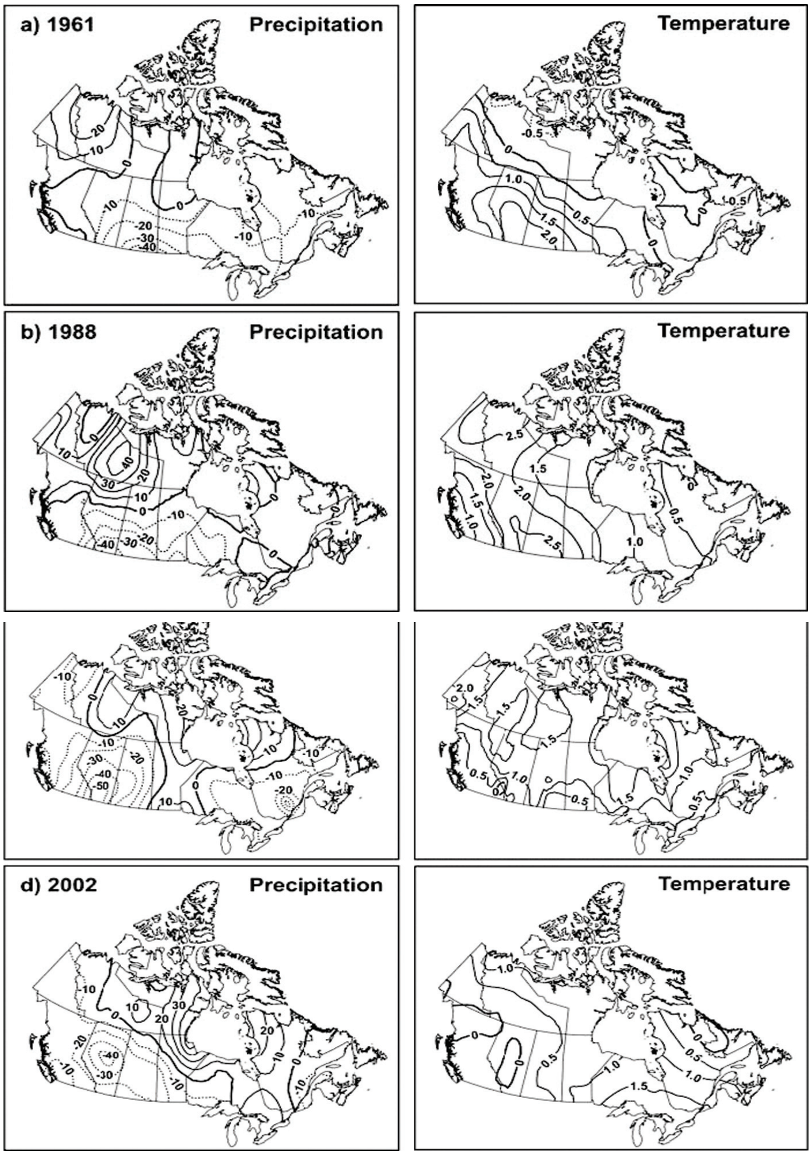


**Figure 2**. Average precipitation departures from normal and temperature anomalies over Canada for the autumn to summer period associated with the droughts of a) 1961, b) 1988, c) 2001, and d) 2002. Units are °C for temperature and percentage departures for precipitation, both relative to the 1961-1990 period. Negative values are dashed.

surface temperatures. This was certainly the case in 1961 and 1988, which ranked as the two hottest summers on the Prairies since regional records began in 1948. The absence of strong ridging in 2001 and 2002 likely explains why these years did not have the extreme warm summer temperatures that are common to many Canadian Prairie droughts. These temperature differences are reflected in Figure 2, which shows that the 1960 and 1988 droughts were similar: temperatures were 1.5°C to 2.5°C above normal over most of the Prairies. The 2001-2002 drought years, on the other hand, did not experience extreme warm temperatures over the Prairies, with values averaging 0.5°C to 1°C above normal. In fact, in 2002 the Prairies experienced their coldest spring on record since regional records began in 1948.

In terms of teleconnections, it was found that the beginning of the 2001 and 2002 drought periods was associated with a La Niña event (it ended in the winter of 2001), while the spring and summer of 2002 saw the beginning of an El Niño event that continued into the winter of 2003. In 1988, there was a strong El Niño event prior to the drought. The 1961 drought, on the other hand, was associated with the absence of El Niño or La Niña events prior to or during the drought. The preceding therefore indicates no consistency in terms of El Niño and La Niña events during these major droughts. Over the North Pacific Ocean, the 2001-2002 drought period was associated with a SST pattern consistent with a negative PDO, which is opposite to the positive PDO observed during 1961 and 1988. A positive PDO pattern was prevalent during most of the 1980s,

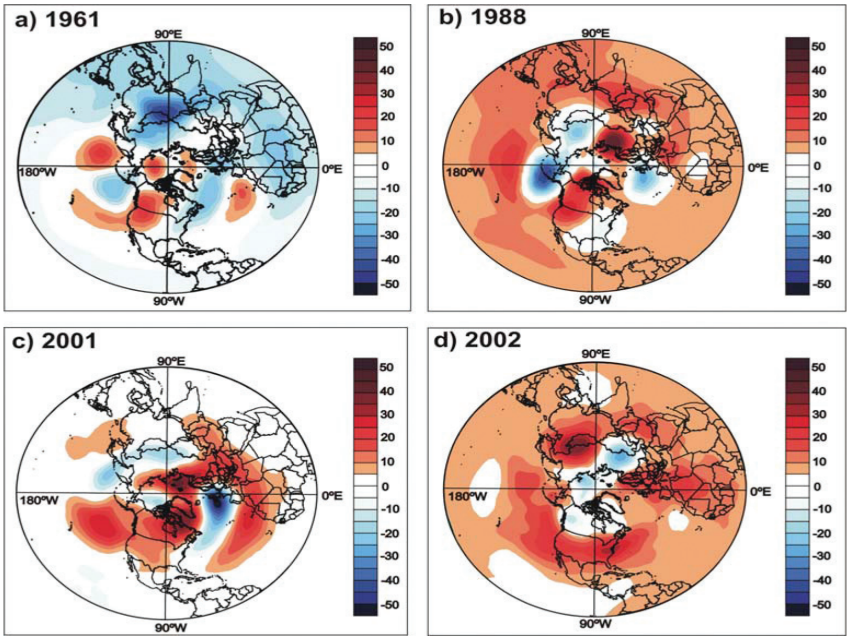


**Figure 3**. Average Northern Hemisphere 500 hPa geopotential height anomalies for the autumn to summer period associated with the droughts of a) 1961, b) 1988, c) 2001, and d) 2002. Units are in metres and anomalies are relative to the 1948-2002 period.

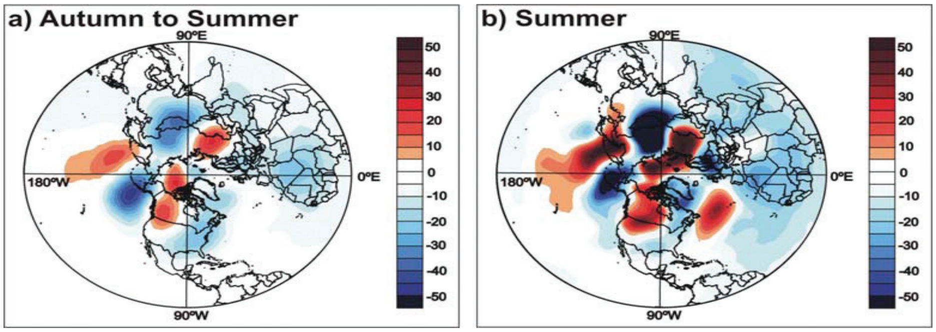


**Figure 4**. Difference in Northern Hemisphere 500 hPa circulation between the 1961 and 1988 droughts and the 2001 and 2002 droughts (1961 and 1988 minus 2001 and 2002) for a) autumn to summer and b) summer. Units are in metres.

which was considered a dry decade for much of the Prairies. Note that preliminary analysis indicates that a persistent positive PDO pattern was associated with the major Prairie droughts of the mid-1930s. Therefore, the North Pacific SSTs during 2001-2002 differed from those associated with previous dry periods in Western Canada.

## Implications of the Results

Our research found that upper atmospheric circulation patterns and teleconnections during the 2001 and 2002 Canadian Prairie drought years were somewhat different from those associated with the severe, multi-season droughts of 1961 and 1988.

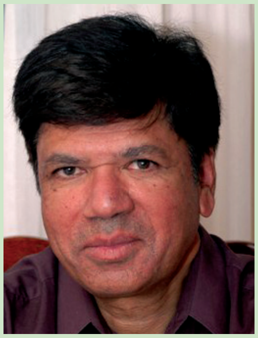
These differences have implications for long-range forecasting of Prairie droughts and signify that further research is required to determine the range of large-scale circulation patterns responsible for extended dry periods over the Canadian Prairies and the rest of North America. These other areas of research should include the role of Atlantic SSTs, which have been associated with drought conditions in both Canada and various regions of the United States, as well as the role of soil moisture, which has been shown to affect atmospheric circulation patterns in drought-prone regions. Atmospheric circulation patterns and teleconnections associated with extreme wet periods on the Prairies, which have received little attention when compared to droughts, should also be identified to determine similarities and differences with major drought episodes.

This research has provided insight into the large-scale atmospheric circulation patterns associated with the 2001 and 2002 Canadian Prairie drought years. The differences with other droughts indicate that more research is needed to better understand the atmospheric causes of large-area droughts over Canada and North America. These new insights could aid in the long-range prediction of severe dry episodes in these regions.

*Atmospheric Sciences*

# SEA SURFACE TEMPERATURES AND THEIR INFLUENCE ON DROUGHT PATTERNS ON THE CANADIAN PRAIRIES

*Amir Shabbar*



*A graduate of the University of Toronto in Meteorology, Amir Shabbar has carried out research in climate variability and prediction for nearly 30 years with Environment Canada. Amir's specialty is large-scale atmospheric and oceanic teleconnections and their effect on the Canadian climate. Amir's research investigation of the El Niño-Southern Oscillation (ENSO) phenomenon forms the basis of the understanding of ENSO's impact on the Canadian climate. Amir's award-winning websites on El Niño and La Niña are authoritative sources for Environment Canada on ENSO. His teleconnection work has also enhanced our understanding of the North Atlantic Oscillation and the Pacific Decadal Oscillation as they affect the Canadian climate. Amir has carried out innovative research in spatial statistics using the Canonical Correlation Analysis technique to design, develop, and implement an operational statistical seasonal forecast model for Canada. Amir has used his expertise in spatial statistical analysis to document the effects of ENSO on drought, large-scale forest fires, and Canada's severe 1998 ice storm. Amir's collaboration with university and international scientists has produced a long list of publications in peer-reviewed journals. He was awarded the 2006 Andrew Thomson Prize in Applied Meteorology by the Canadian Meteorological and Oceanographic Society.*

## Introduction

Drought can be described as an extended shortfall of precipitation that results in inadequate water supply to meet the needs of humans and the environment. As a routine part of the natural hydrologic cycle, the Canadian Prairies experienced a number of major droughts during the twentieth century. The continental-scale droughts in the 1930s and 1950s lasted for a number of years and a number of proxy climate records indicate that multi-year droughts were a regular feature of the Canadian Prairie climate over the course of at least the past 400 years.

Recent advances in numerical modelling have contributed to our understanding of some of the important processes during prolonged droughts. The mechanisms by which a drought can be maintained over many years, however, are not very well understood. Severe large-spatial-scale North American droughts over the past century have had a tendency to cluster in successive years and are likely related to large-scale forcing from the atmosphere-ocean variability on a similar time scale. For example, the recent 1987-1989 and 1999-2005 droughts are suggestive of ocean forcing on similar temporal scales. The change in the balance between precipitation and evaporation is caused by changes in atmospheric circulation and is most likely teleconnected to long-term ocean variability. It is important to understand dynamical and statistical relations between slow-varying global Sea Surface Temperatures (SSTs) and warm season moisture availability over the Canadian Prairies.

## Palmer Drought Severity Index

Several drought indices related to different aspects of drought intensity, duration, and persistence have been developed. The Palmer Drought Severity Index (PDSI) is the most commonly cited index and forms a component of the North American Drought Monitoring System. The PDSI is a standardized index that allows for a comparison of drought conditions with different local and regional climatology. The PDSI is a soil moisture accounting algorithm based on water balance and is derived from ongoing measurements of precipitation, air temperature, and local soil moisture. The index, in any given season, is a function of climatic and soil moisture conditions occurring in the current and preceding seasons. The PDSI reflects long-term moisture, runoff, recharge, deep percolation, and evaporation and contains persistence from the previous season. It is aptly suited to drought analysis over time spans of seasons or years.

## Interannual and Interdecadal Oceanic Indices

The dominant source of interannual variability in the Canadian climate originates from the El Niño-Southern Oscillation cycle (ENSO) phenomena in the tropical Pacific Ocean. ENSO occurs at irregular intervals of two to seven years and lasts nine months to two years (see time series of tropical SSTs, Figure 1, T1). During El Niño events, anomalous heating in the overlying atmosphere associated with warmer-than-normal waters in the eastern tropical Pacific produces above-normal rainfall in the

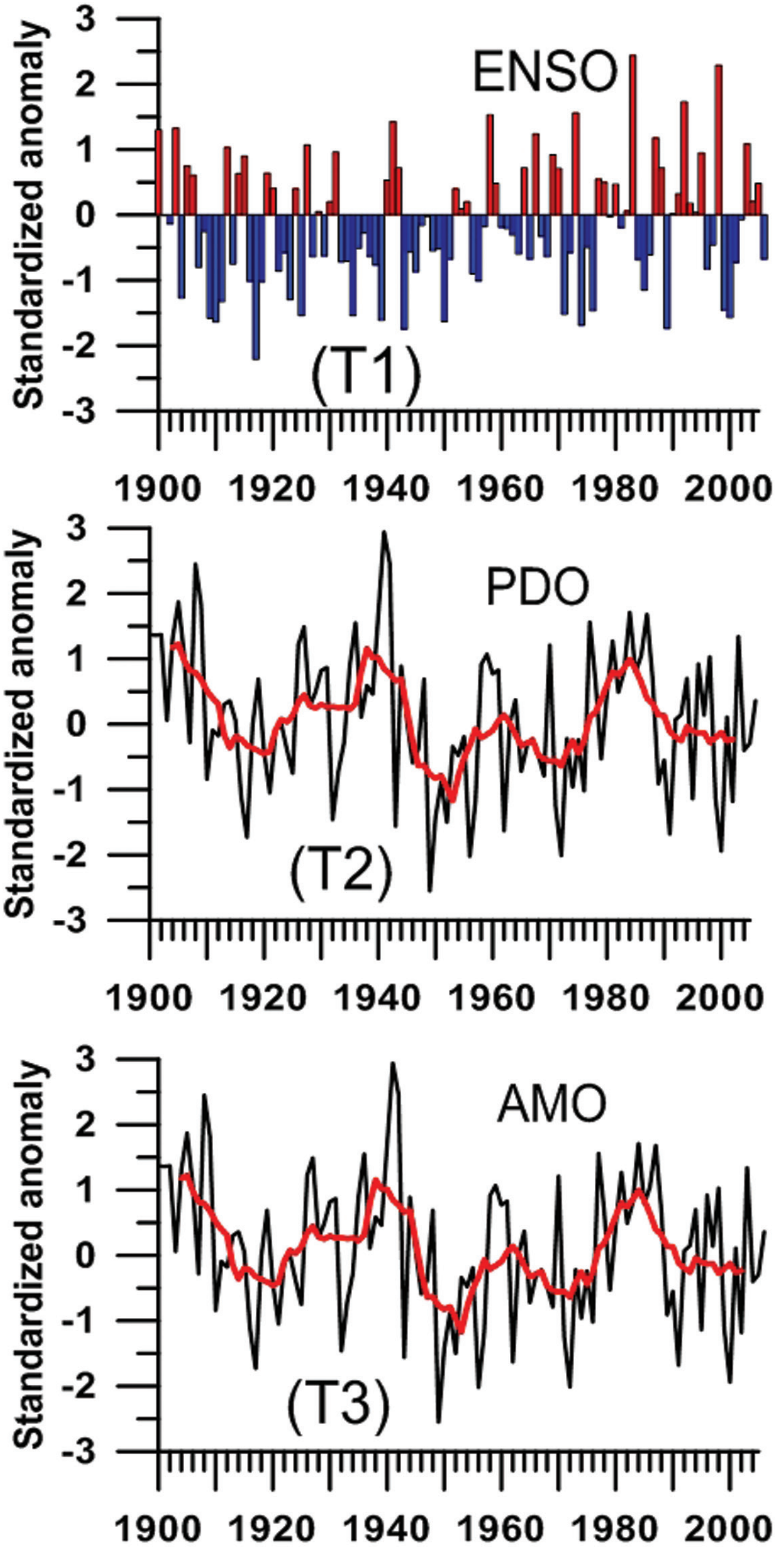


**Figure 1**. The time variations in indices of: (T1) ENSO defined as average SST anomaly between (5ºN-5ºS, 120ºW-170ºW); (T2) PDO defined as leading mode of SST anomaly in the North Pacific, north of 20ºN; and (T3) AMO defined as SST anomaly in the North Atlantic.

tropical Pacific. The resulting release of latent heat favours the generation of Rossby waves, which defines one of the principal modes of variability in the Northern Hemisphere circulation – the Pacific North American (PNA) teleconnection. The PNA has one of its strongest centres of action over Western Canada. It is therefore of paramount importance that we understand the role of interannual and interdecadal oceanic anomalies in the initiation and maintenance of extended droughts in Canada. Evidence for a lagged relationship between warm season climate variability in North America and preceding winter tropical SSTs is found in observational data. A strong relationship between seasonal Canadian temperature and precipitation, key factors in the formation of drought, and ENSO has previously been established. Currently, the ENSO cycle constitutes a major source of skill in the seasonal prediction of temperature and precipitation in Canada.

In the North Pacific, multi-year variation in SSTs is captured by the Pacific Decadal Oscillation (PDO; Figure 1, T2). The PDO, which is an ENSO-like climate oscillation defined as the leading low frequency mode of SST variability north of 20°N, shifts phases on an interdecadal time scale and has been shown to produce climate anomalies downstream over North America. Another source of North American climate variability originates from the North Atlantic Ocean. Study of long-term historical data indicates that the North Atlantic climate is dominated by a single mode of North Atlantic SST variability. An important characteristic of this mode is that SST anomalies have the same sign across the entire North Atlantic and resemble the Atlantic Multidecadal Oscillation (AMO). The AMO is an oceanic phenomenon with a long time-scale of 65-80 years and a range of 0.4°C (Figure 1, T3). The AMO has been shown to affect precipitation in the United States. The multidecadal behaviour of the AMO also asserts its influence on long-term drought predictability in Canada.

## Methodology

The spatial statistical technique of Maximum Covariance Analysis (MCA) is used to determine the spatial and temporal variability of summer moisture availability in Canada as it relates to global SSTs. MCA aims to isolate linear combinations of variables within two fields that tend to be linearly related to one another. A conceptual advantage of MCA over other pattern-matching techniques is that it directly produces explicit measures of relatedness among the derived coupled patterns. Prior to the MCA, PDSI and SSTs are decomposed into their respective orthogonal components. The leading ten low-frequency components of both PDSI and SSTs form the input into the MCA model. Specifically, MCA maximizes covariance between summer (June to August) PDSI and previous winter (December to February) global SSTs by decomposing their covariance matrix into singular values and two sets of paired orthogonal vectors – one for each field. The strength of their association is measured by the squared covariance fraction. The teleconnection between the two fields is revealed by spatial patterns of correlation, which are defined as the serial correlation between the expansion coefficient of one field and the grid point anomaly values of the other field.

## Results

Results of the MCA between winter global SSTs and following summer PDSI over Canada show that the leading three MCA-coupled modes explain over 80% of the squared covariance fraction. The first MCA mode strongly relates to the trend in global SSTs as well as multidecadal variation of the North Atlantic SSTs, explaining one-third of the squared covariance (Figure 2, S1 pattern). It is reflective of both the warming trend, with positive loadings throughout the southern global oceans, and the influences of the AMO variability. The associated standardized time series shows considerable interannual variability with a strong positive trend.

The interannual ENSO, the interdecadal PDO, and the interrelationship between the two are prominent in the second and third MCA modes. Together, these Pacific Ocean processes explain nearly 48% of the squared covariance. The S2 pattern (Figure 2) identifies strong loadings in the tropical Pacific related to the ENSO phenomenon. The time evolution of this pattern shows extremes in El Niño and La Niña years. The third MCA modes (Figure 2, S3) relates to the interdecadal PDO signature with strong positive loadings in the North Pacific. This pattern also contains a weaker component of the interannual ENSO cycle. The time series associated with this mode reflects the climate shift in the North Pacific corresponding to the 1976-1977 regime change.

In order to understand teleconnectivity between these modes of winter SST variability and the following summer PDSI values over Canada, spatial correlation patterns of PDSI are formed by correlating SST time series with the grid point values of the PDSI. The resulting PDSI pattern (Figure 3, C1) with the first MCA mode shows a deficit in the PDSI in an area stretching from the southern Canadian Prairies to central Quebec. Thus, long-term warming of the southern oceans and cooling in the North Atlantic lead to summer moisture deficits in the southern Canadian Prairies.

The second MCA mode relating to the ENSO cycle shows that the warm phase of ENSO produces a negative anomaly in

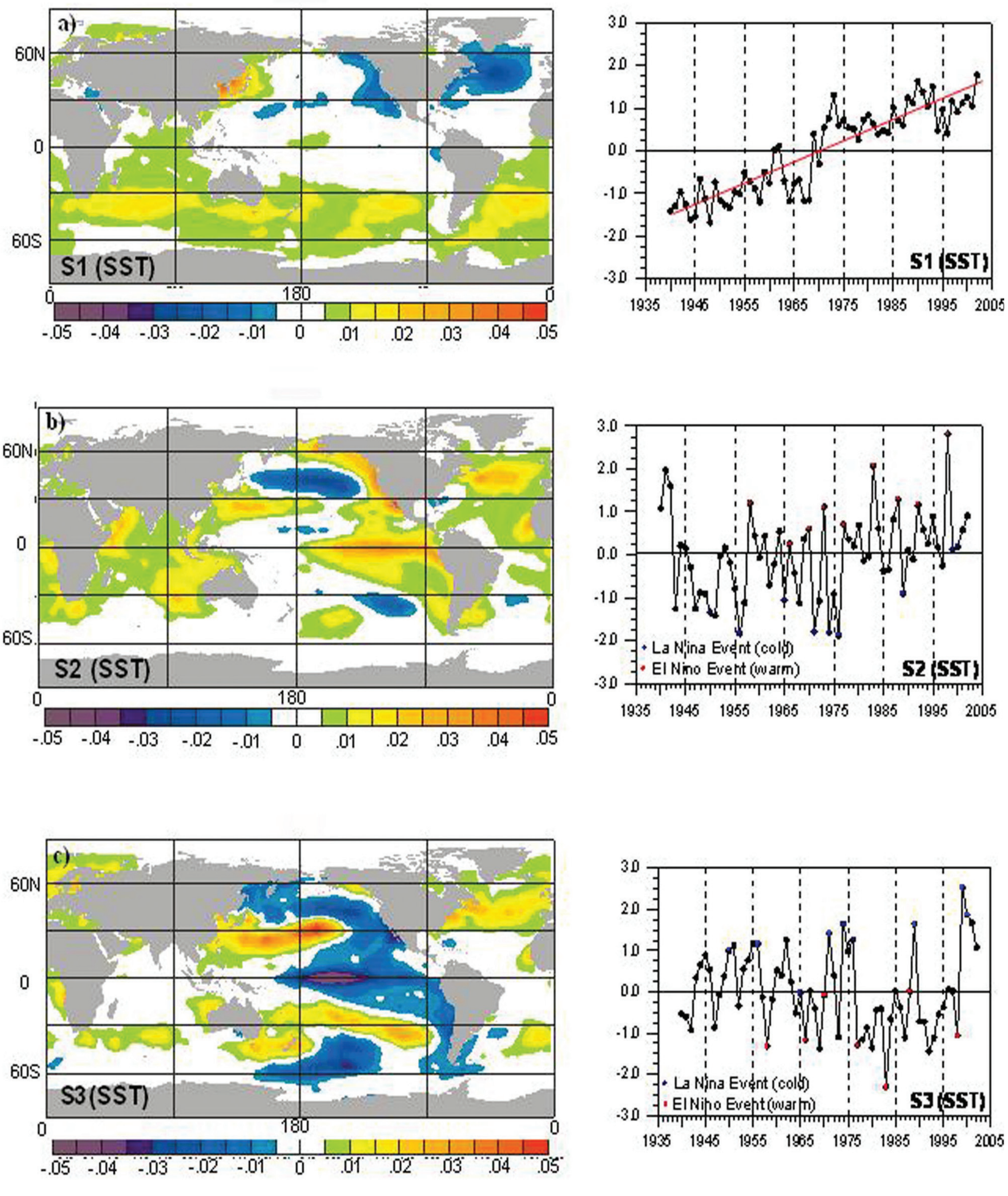


**Figure 2**. The time variations in the MCA pattern of SST and the standardized amplitude based on data for 1940-2002 winters (Dec-Jan-Feb) for: (a) the first MCA pattern (S1) of SST; (b) the second MCA pattern (S2) of SST; and (c) the third MCA pattern (S3) of SST. El Niño and La Niña years are indicated by red and blue dots, respectively, in standardized amplitude.

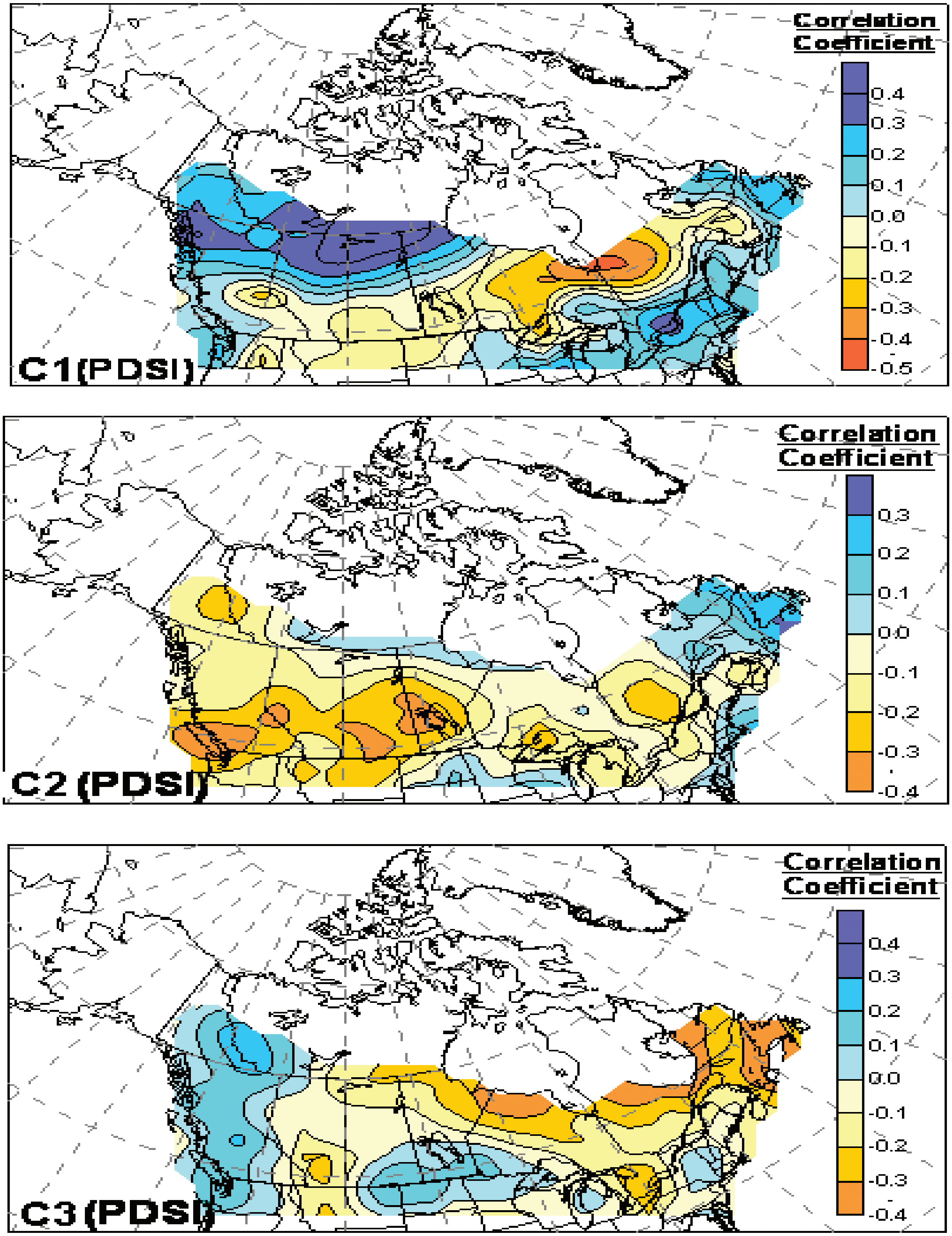


**Figure 3**. The spatial correlation pattern found by relating the PDSI with: (a) the amplitude of first MCA SST; (b) the amplitude of second MCA SST; and (c) the amplitude of third MCA SST.

summer PDSI over western and central Canada (Figure 3, C2). Conversely, La Niña leads to an abundance of summer moisture in Western Canada. The third MCA mode shows that the negative phase of the PDO, along with the cold phase of ENSO, leads to higher summer PDSI values in British Columbia and the south-eastern Prairies, but negative PDSI values over western areas of the Prairies.

During the extended two-year La Niña winters of 1998-2000, SST anomalies in the North Pacific closely resembled the third MCA mode (Figure 2, S3). Warmer-than-normal SSTs in the north central Pacific and colder-than-normal SSTs (resembling the La Niña phase) in the central tropical Pacific Ocean persisted throughout the two-year period. This configuration of the Pacific Ocean SST helped maintain severe drought conditions in the Western Canadian Prairies but brought abundant moisture to southern Manitoba. The severe dry conditions in the western Prairies were a northward extension of a widespread drought in the western United States.

The warming of the southern oceans, particularly the western tropical Pacific and the Indian Ocean, identified by the leading MCA mode of SSTs, has been partly attributed to the build-up of greenhouse gases in the atmosphere. The six-month lag relationship between the PDSI and large-scale SSTs provides a basis for developing long-range forecasting schemes for the occurrence of drought in Canada. This predictability may be further enhanced by the inclusion of direct measurements of snow cover as well as regional information, such as soil type, its characteristics, and vegetation, all of which provide additional information independent of large-scale SSTs. A two-tier forecast scheme, in which the SST is predicted by an ocean model or a coupled climate model, can potentially further increase the lead time of drought forecasting.

### Implications of the Results

Drought is a complex phenomenon causing harm to regional economic and social systems. At times, droughts can persist for years and have impacts on national and international scales. Invariably, meteorological factors are involved in drought, but prolonged droughts are influenced by variations in global SSTs. Thus drought early warning is rooted in ocean observations and accurate SST observations are essential to skilful drought predictions. Useful predictions of the onset, intensity, continuation, and termination of drought would enable more intelligent adaptation to droughts. The results presented here show that long-term changes in the global oceans, in response to global climate change, can lead to moisture deficits, which in turn increases vulnerability to drought in the grain-growing areas of Canada.

The interannual El Niño-Southern Oscillation, the Pacific Decadal Oscillation, and the interrelationship between the two also play a prominent role in the determination of summer moisture availability in the western two-thirds of Canada. Presently, there are at least a dozen statistical and numerical models predicting the onset of ENSO a few seasons in advance. By improving prediction skill from these models, relevant societal sectors can take advantage of early warnings of impending drought and take defensive measures to plan and mitigate its effects.

Canada's increasing dependence on drought-sensitive renewable resources (e.g., water, forests, and soil) requires foreknowledge of droughts for planning and mitigating purposes. With land use changes and a burgeoning population, there is an increased demand for water by all sectors of the economy. This study underscores the importance of oceans as an influence on atmospheric circulation. The attendant teleconnections to Canadian climate can be useful in the development of science-based water resource assessments for effective drought forecasts, management, and mitigation strategies for Canada.

*Atmospheric Sciences*

# WATER CYCLING AND HYDROCLIMATE EXTREMES ON THE CANADIAN PRAIRIES

*Kit K. Szeto*

*Dr. Kit Szeto is a Research Scientist at the Climate Research Division of Environment Canada. He has wide-ranging research interests in the analysis and modelling of weather and climate systems. His recent research focuses on the quantification, modelling, and diagnosis of water and energy cycling processes in Canadian regions. He has published extensively on the assessment of regional water and energy budgets and on theoretical studies of physical mechanisms that govern regional climate variability, including the developments of climate extremes such as droughts and pluvials.*

## Introduction and Motivation

An enhanced understanding of the causal mechanisms that determine the Prairie hydroclimate's response to large-scale forcings is essential to improving the dynamical predictions of droughts and pluvials in the region. The climate variability of a region depends critically on the exchange of water and energy between the region and its environment and on the internal cycling and conversion of these quantities within the region. Hydroclimate extremes such as extended droughts might occur when the water and energy balance that characterizes the mean climatic state of a region is seriously disturbed by either changes in external forcings, such as large-scale circulation, or regional factors, such as land use. Hence, quantitative assessments of components of water and energy fluxes and reservoirs, including their temporal and spatial variations, continue to be an important first step in characterizing, understanding, and predicting the climate, including the occurrence of climatic extremes, in a region. One of DRI's major scientific activities has been to develop comprehensive assessments of the water and energy budgets for the Prairie region.

This article will first give an overview of the methodology and datasets used in the DRI water and energy budget study, along with a brief account of the main findings. The results will be analyzed to gain new physical insights into the myriad interacting processes that govern the interannual variability of warm season precipitation in the region. In particular, we will consider how pluvial and drought episodes might develop when these processes are perturbed by responses to changes in larger-scale conditions.

## Methodology and Datasets

Details of the methodology and datasets employed in the comprehensive assessments of water and energy budgets for the Prairie region can be found in Szeto (2007) and Szeto et al. (2010b). In those studies, data from state-of-the-art models such as the Canadian Regional Climate Model (CRCM), data assimilation systems, remotely-sensed or blended datasets, and observations are analyzed to provide several quasi-independent estimates of the water and energy budgets.

Apart from the development of comprehensive climatologies of budgets for the Prairies, the relative merits of the different models and commonly used climate datasets in representing the water and energy cycle of the region were also assessed through cross-validations. For example, the National Centers for Environmental Prediction - Reanalysis 2 (NCEP-R2) dataset, commonly used in climate studies, excessively over-predicts water cycling for the region. On the other hand, the European Centre for Medium-Range Weather Forecasting (ECMWF) 40-year Reanalysis (ERA-40) dataset gave the best overall representation of water and energy cycling in the Prairie region among commonly available long-term reanalysis datasets.

Based on the results of budget inter-comparisons, a dataset from various sources was selected to produce long-term (1960-2002) monthly time series of atmospheric water budgets to use when studying the temporal variability of water budgets and exploring the statistical and physical relationships between these variables. In particular, surface evapotranspiration (represented by E) and atmospheric moisture flux convergence (MC) were computed from the ERA-40 reanalysis data. Precipitation (P) was obtained from the CANGRID dataset and synthetic soil moisture (SM) data was obtained from the Variable Infiltration Capacity hydrological model (VIC) simulations (Lin and Wen, this volume).

## Results and Findings

### Seasonal Variability of Prairie Water and Energy Budgets

A brief description of the water and energy cycle of the Saskatchewan River Basin, which covers much of the Canadian Prairies, will be given here. Like other mid- to high-latitude continental regions, the Basin acts as a sink region for heat and water in the global climate system. During the boreal cold season, when the mean north-south temperature contrast is strong and the atmosphere is dynamically active in the northern hemisphere, a large amount of heat energy is transported into the Basin from the warm southern and oceanic regions. The region receives little solar radiation during these months and the atmospheric heat convergence into the Basin is largely balanced by thermal radiation loss to outer space during winter.

Although the strong mean westerly flow entering the continent from the North Pacific is moisture-laden, much of the moisture is precipitated out of the atmosphere over the coastal mountainous regions. Consequently, net moisture flux convergence into the basin is typically weak throughout the year (see MC in Figure 1). During the cold season, precipitation (P) is relatively low and comes solely from synoptic systems that pass over the Basin. As surface evaporation is weak, the winter precipitation is largely balanced by the large-scale moisture convergence into the Basin (Figure 1). Winter precipitation often falls in the form of snow because of the low winter temperatures. Due to the flat terrain and land covers that characterize the region, strong winds are common during the winter; wind transport and enhanced sublimation in the blowing snow can account for the loss of up to 40% of winter precipitation over the region (Pomeroy and Essery, 1999). In addition, enhanced sublimation and melt during Chinook events can occur over the south-western Basin. As a result, although winter precipitation amount is similar between the Saskatchewan River Basin and some more northern basins such as the Mackenzie Basin, snow accumulation is typically much lower and more variable between years on the Prairies at the end of winter.

Solar insolation increases and warms the surface during spring. A substantial portion of the solar input melts snow on the surface. The meltwater often recharges the soil in many areas of the Basin. Due to the "pothole" topography characteristic of the region, surface water bodies of various sizes could form from the spring melt.

The dry lee-side subsiding mean flow allows the Basin to experience abundant solar insolation during the summer. As a large portion of the Basin's surface is covered with vegetation, wet soil, or surface water bodies, much of the solar insolation is consumed in evapotranspiration processes, which induce large water fluxes from the surface (see E during May-August in Figure 1). A relatively smaller portion of the solar radiation is used to warm the surface, which in turn warms the lower atmosphere via sensible and turbulent heat transfer. The surface heat and moisture fluxes destabilize and moisten the atmosphere. Consequently, the majority of warm season precipitation in the

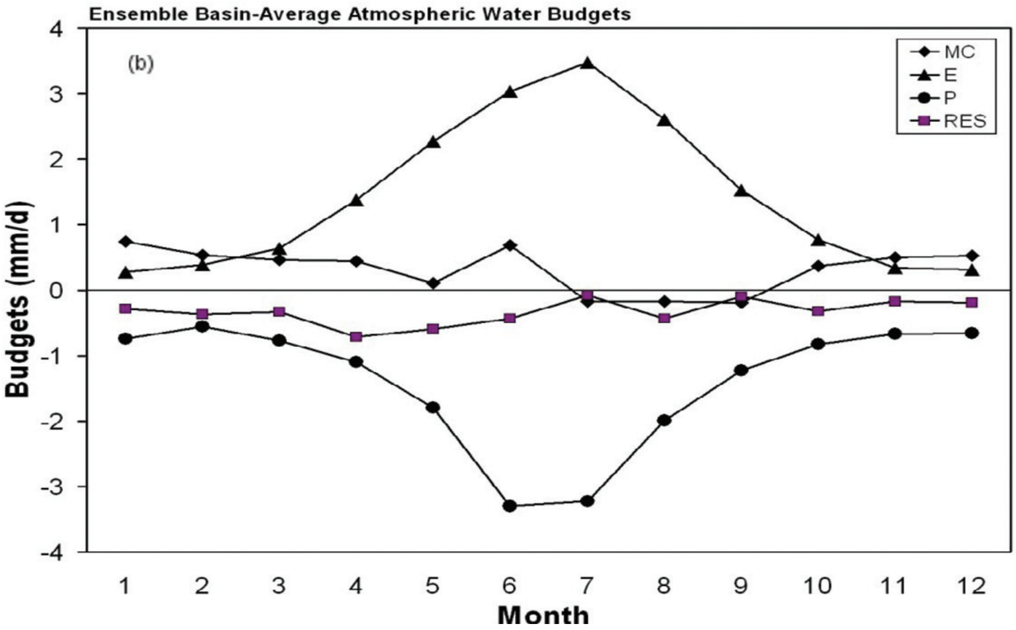


**Figure 1**. Mean annual cycle of ensemble (NCEP-R2, ERA-40, Canadian Meteorological Centre, and CRCM) basin average atmospheric water budgets for the Saskatchewan River Basin. MC, E, P, and RES denote, respectively: moisture flux convergence, evapotranspiration, precipitation, and budget residual.

region is convective in nature (Raddatz and Hanesiak, 2008). The considerable evapotranspiration and precipitation (and their strong phase coherence) that characterize the Basin during the warm season (Figure 1) suggest that moisture recycling might play an important role in governing the warm season water cycle of the region. The inference was partially supported by results in a study by Raddatz (2000) which showed that moisture from local evaporation could account for 24% to 35% of the total summer rainfall over the Canadian Prairies.

In summary, the highly variable snow cover provides a potential linkage between winter and summer Prairie water cycling processes through its effects on spring recharge and air-land coupling during the warm season. Although evapotranspiration is large enough to account for warm season precipitation in the region, the background subsiding cross-barrier flow is detrimental to precipitation development. In fact, much of the evaporated moisture is transported out of the area through the unobstructed southern and eastern boundaries by the mean northwesterly flow, which turns the Prairies into a moisture source (i.e., MC is negative in Figure 1) during the summer. The effects of the interplay between these processes in governing the warm season precipitation and its variability over the Prairies will be examined next.

## Interannual Variability and Prairie Hydroclimate Extremes

In order to examine the temporal variability of water budget components and explore the statistical and physical relationships between these variables, long-term (1960-2002) monthly time series of atmospheric water budgets were computed for different regions over the Prairies using various source data (described earlier; see also Szeto, 2010). Since drought is generally more frequent and most severe over the central and western Prairies (e.g., within the Palliser Triangle), we will focus on results for the Prairie region west of 255°E. Much of the discussion will nevertheless also apply to the eastern Prairies.

Table 1 shows the contemporaneous correlation coefficients between the variables for the month of June within the 43-year period. While there is some intra-seasonal variability in the correlation results, the results in Table 1 are quite representative for individual months within the season (Szeto, 2010). Several notable relationships between Prairie water cycling processes are revealed in the results. First, despite the fact that evapotranspiration and soil moisture were obtained from different data sources, they are positively and significantly correlated, suggesting that evapotranspiration on the monthly time scale is strongly controlled by surface water availability on the Prairies. Second, although the positive correlation between precipitation and soil moisture is statistically significant, the correlation is relatively weak, a result which presumably reflects the persistence or memory effects of deep soil moisture on these time scales. Given the active evapotranspiration during the warm season and its almost identical seasonal variation with precipitation in the region (Figure 1), the most striking result may be the low covariance between the two on the monthly time scale. On the other hand, although the magnitude of moisture flux convergence is relatively low when compared to either precipitation or evapotranspiration, precipitation is strongly and positively correlated with large-scale moisture flux convergence into the region.

| | P | E | MC | SM | C |
|---|---|---|---|---|---|
| **P** | 1 | -0.05 | 0.80 | 0.31 | 0.67 |
| **E** | -0.05 | 1 | -0.21 | 0.60 | -0.07 |
| **MC** | 0.80 | -0.21 | 1 | 0.06 | 0.60 |

**Table 1**. Contemporaneous correlation coefficients between various water budget terms averaged for the month of June over the western Prairies. Correlations that are significant at the 95% level are highlighted.

Insights into the Prairie water cycle could be gained when the statistical results are interpreted with knowledge of the hydrometeorological processes that occur in the region. The weak relationship between precipitation and evapotranspiration largely reflects the fact that a large portion of the evaporated moisture is transported out of the region by the cross-barrier mean subsiding flow instead of being used in producing precipitation within the area. Hence, strong positive feedback between regional precipitation, evapotranspiration, and soil moisture is unlikely over the Prairies under normal conditions. On the other hand, the surface moisture flux is essential in destabilizing the lower atmosphere to facilitate the development of convective precipitation and local moisture was also shown to contribute significantly to precipitation in the region (Raddatz, 2000). These aspects, when considered together with the statistical significant correlations between soil moisture and precipitation and evapotranspiration, indicate that negative feedback between these processes is plausible over the Prairies. For example, dry soil in the spring following a dry winter could contribute to the development of drought during the growing season.

Hence, although there is abundant atmospheric moisture from local evaporation, atmospheric flow processes that could counteract the subsiding background flow and provide atmospheric lifting to overcome the inversion at the top of the boundary layer and trigger convection are required for precipitation development. Examples of those processes include the local upslope mountain plains circulation that develops over

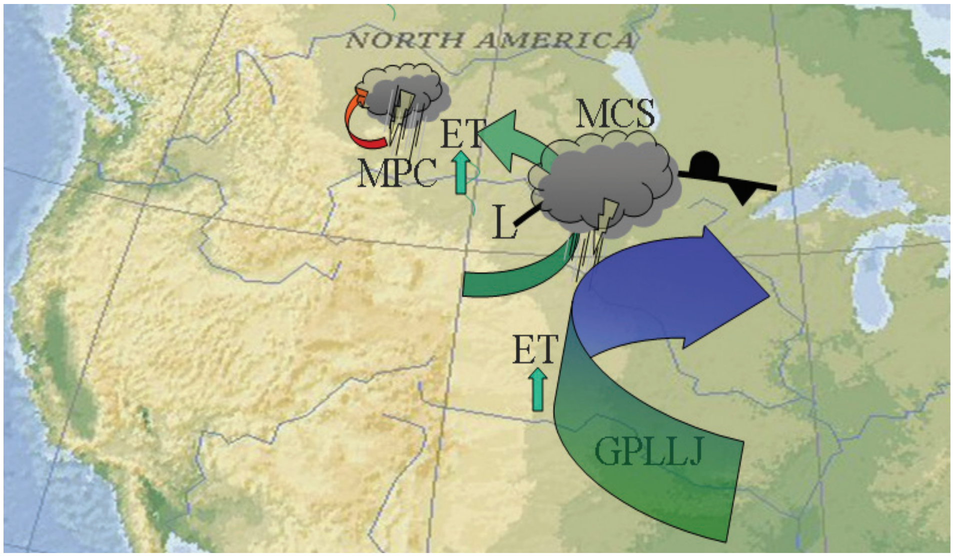


**Figure 2**. Schematic illustration of how low-pressure systems over the central Plains and southern Prairies could enhance moisture transport and precipitation on the Canadian Prairies. GPLLJ, ET, MCS, MPC, and L denote, respectively: the Great Plains low-level jet, evapotranspiration, mesoscale convective system, mountain-plains circulation, and surface low pressure centre.

the foothills during sunny days, flow convergence at drylines that separate the dry subsiding air off the foothills and the moist air over the plains (Strong, this volume), and upward motions induced by the synoptic storm features that develop in the vicinity of the area. While these processes could have an effect on moisture flux convergence into the region, we will show that the interannual variability of large-scale moisture flux convergence into the Prairies is governed mainly by synoptic activities.

Figure 2 presents a conceptual model that summarizes how low pressure systems over the southern vicinity of the Prairies may affect moisture transport and precipitation development in the region. First, the cyclonic flow at low levels counteracts the background northwesterly divergent flow and bounds the moisture from local evaporation to remain within the Prairies. Second, it transports moisture into the eastern Prairies from the south. In particular, it relays the moisture that is transported into the central United States by the Great Plains low-level jet into the Canadian Prairies. Such external moisture supplements local moisture during normal and wet periods and may well be the main source of moisture for precipitation during dry periods. These systems also provide the lifting mechanisms to trigger convection through frontal lifting for organized mesoscale convective systems to develop over the eastern Prairies. Over the western Prairies, the easterly cyclonic flow and associated moisture transport could induce orographic precipitation or enhance the mountain-plains circulations or dryline developments.

The critical effects of such synoptic systems on moisture flux convergence and precipitation on the Prairies are made evident by the strong correlations between these variables and the C-index (Table 1). The C-index is defined by the product of lower-level southerly moisture transport in the region just south of the eastern Prairies and the easterly lower-level moisture transport over the central Prairies (see Szeto, 2010 for details). The index gives a measure of the moisture transport by cyclonic airflows into the eastern Prairies from the south and into the mountains from the east. Higher monthly or seasonal values of C indicate a higher frequency of cyclonic systems, or the occurrence of strong systems, over the southern vicinity of the Prairies for the period.

These results suggest that although local moisture plays an important role in the development of warm season precipitation over the Prairies by modifying the atmospheric conditions to facilitate convection and constitutes a significant source of moisture for the precipitation, the interannual variability of warm season precipitation is governed mainly by the synoptic systems that occur over the southern vicinity of the area. Based on these analyses, we hypothesize that pluvial periods in the region are associated with an anomalously high frequency of such cyclonic systems. Extended dry periods over the Prairies are caused by the lack of these systems. Extreme multi-year drought conditions are caused by low soil moisture and evapotranspiration from low winter precipitation, which occur in conjunction with a low frequency of favourable synoptic systems during the warm season.

## Past Extreme Wet and Dry Episodes

In this section, we examine how well the hypotheses could

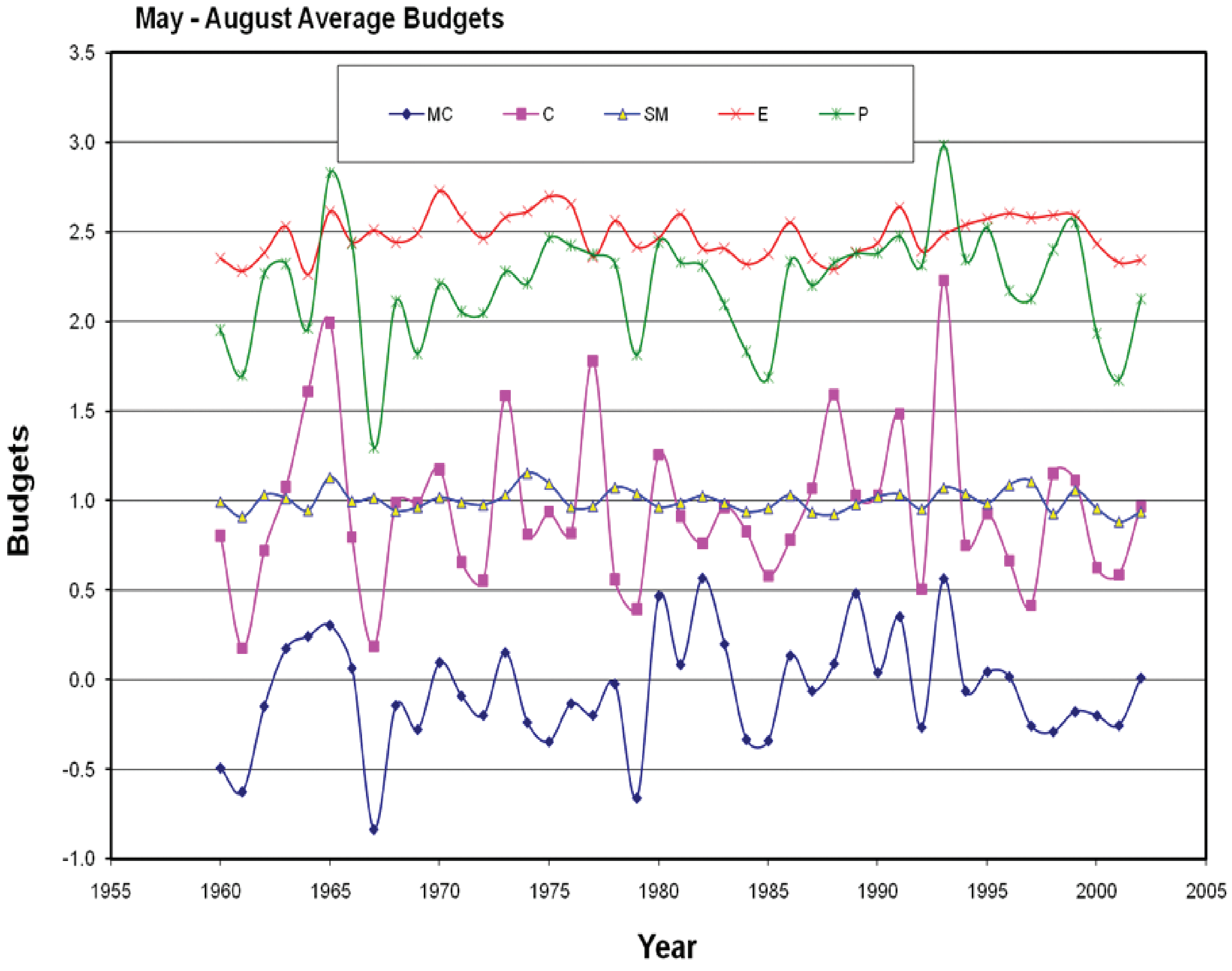


**Figure 3**. Timeseries of May-August average of some water budget terms for the western Prairies. P, E, and MC are in mm $d^{-1}$ and SM and C are rescaled to fit within the plotting area.

account for the water cycling processes that characterized past major Prairie pluvial and drought periods. Figure 3 shows the 1960-2002 timeseries of growing season (May to August) average of selected water budget terms for the western Prairies. During the 43-year period, there were two extreme wet growing seasons (1965 and 1993) and five extreme dry seasons (1961, 1967, 1979, 1985, and 2001). Results in Figure 3 show that both wet years were characterized by extremely high values of the C-index and associated anomalously high moisture flux convergence into the region. While 1965 was characterized by anomalously high evapotranspiration, 1993 was characterized by close-to-average values. On the other hand, all the extreme dry years were characterized by anomalously low storm activities and associated low moisture flux convergence values but varying E conditions. Evapotranspiration was low during 1961 and extremely low during 2001; both are among the worst drought years within the period. Both 1961 and 2001 were characterized by lower-than-average winter precipitation, which resulted in reduced spring soil moisture recharge to support normal evapotranspiration during the warm season. In fact, precipitation for the 2000-2001 winter was the lowest among the 43 years. All other three dry years were characterized by close-to-normal E during the growing season. It is of interest to note that the winter precipitation for 1967 was among the highest for the 43-year period. Years with substantially higher than normal winter precipitation (1972, 1974, 1997) were all characterized by relatively dry summers due to low storm activity and moisture flux convergence.

These results generally support our inference about the effects of the interplay between winter and summer processes and between regional and larger-scale processes on warm season precipitation over the Prairies. Yet some anomalous seasons did not conform to the predictions. The year 1988, for example, is a well-known extreme drought year even if its growing season precipitation was not particularly low in Figure 3. In terms of the sub-seasonal variability of water budgets for the year, 1988 was characterized by anomalously low winter precipitation and extremely low soil moisture and evapotranspiration during the spring and summer months. Combined with lower-than-normal moisture flux convergence, precipitation was anomalously low for May and July, as expected. Although June was also characterized by lower-than-normal moisture flux convergence, its precipitation was substantially higher than normal, largely due to a long-lived extreme rain event that affected the western Prairies during the earlier part of the month. A similar extreme rain event also occurred in June 2002, in the midst of the 1999-2005 drought (Szeto et al., 2010a; see also Stewart et al., this volume). In both cases, the extreme rain events were associated with cyclogenesis over the central Plains with conditions similar to those depicted in Figure 2. It is also of interest to note that the seasonal average precipitation for both years was substantially higher than what one might have expected during an extreme drought event.

## Summary and Implications

In this article, we reviewed the water budgets and associated hydroclimate processes for the Canadian Prairies. In particular, we have elucidated the complex interplays between some winter and summer processes and between regional- and larger-scale processes that critically govern the interannual variability of warm season precipitation in the region. Snowmelt from normal winter precipitation would allow the soil moisture to sustain active evapotranspiration during the warm season. Evapotranspiration alone could have provided more than enough moisture to account for the observed warm season precipitation. However, much of the evaporated moisture is transported out of the region by the background subsiding cross-barrier flows instead of being used to feed the precipitation. As a result, transient atmospheric convergent flows associated with synoptic activities, particularly the low-pressure systems that develop over the north-central United States, are important in counteracting the background flow to confine the moisture to remain within the region, to transport additional moisture into the area from the south, and to provide atmospheric lifting mechanisms that trigger convection and precipitation development.

We hypothesize that the interannual variability of warm season precipitation on the Canadian Prairies is governed by synoptic activities that occur along their southern edge. Extreme drought is caused by low soil moisture and evapotranspiration from low winter precipitation in conjunction with a lower-than-normal frequency of favourable synoptic systems during spring and summer. Extremely wet growing seasons, conversely, are the result of an anomalously high occurrence of these systems. The hypotheses seem to be able to account for the development of most of the Prairie pluvial and drought periods examined in this study.

It is generally agreed that hydroclimate extremes on the Prairies are ultimately forced by low-frequency variability in the atmosphere-ocean system. Yet the complex inter-seasonal and cross-scale process interactions that critically affect precipitation on the Prairies, such as those discussed in this paper, obscure its hydroclimatic response to large-scale climate forcings. These effects are also reflected in the weak teleconnection signals that were typically found when relating Prairie hydroclimate variability to variations in large-scale conditions (e.g., Shabbar et al., 2010). Hence, a hierarchical approach that focuses on examining the interactions between processes that occur on critical neighbouring scales should be adopted to address the problem. For example, the physical linkages between continental synoptic activities and changes in large-scale conditions could be more readily explored and understood with established theoretical frameworks. The synoptic systems effectively interface the regional processes to the large-scale forcings. By clarifying the roles of the interaction between these synoptic systems and the regional processes affecting Prairie precipitation, our results fill an important gap in improving our understanding of the causal mechanisms that determine the Prairies' hydroclimatic response to large-scale climate forcings. A greater understanding and improved prediction of the Prairie hydroclimate system could be facilitated by a two-pronged approach to the problem: an exploration of the physical linkages between low-frequency climate forcings and the variability of warm season synoptic activities over the continent; and through further study of the relationship between these synoptic systems and the regional processes that are unique to the Prairies.

*Atmospheric Sciences*

# CLOUDS: DROUGHT RELATIONSHIPS FROM OBSERVATIONS AND A REGIONAL CLIMATE MODEL

*Henry Leighton and Heather Greene*

*Henry Leighton received his B.Sc. and M.Sc. degrees from McGill University and his Ph.D. in Nuclear Physics in 1968 from the University of Alberta. This was followed by a post-doctoral fellowship in the Department of Physics at the University of Utrecht and a visiting faculty appointment in Physics and Astronomy at the University of Kentucky. In 1971 he returned to McGill University, where he joined the Department of Meteorology (now the Department of Atmospheric and Oceanic Sciences). He served as Chair of the Department and as Associate Dean (Student Affairs) in the Faculty of Science. His research interests include aerosols, atmospheric radiation, cloud microphysics, and satellite measurements of radiation budgets.*

## Motivation for the Research

Periods of reduced precipitation must be related to changes in cloud properties during those periods compared to normal conditions. For example, there may be changes in cloud amount, cloud thickness, or clouds' microphysical properties, such as cloud droplet sizes and cloud droplet number concentrations. If we are to understand the drought's causes and the possible feedbacks that may impact its severity and length, we need to understand the ways in which clouds are different during droughts. Numerical models provide useful tools to aid in the understanding of drought. In order to have confidence in their results, however, it is important to test them against observations. It is of particular interest to determine whether the modelled relationships between cloud properties and precipitation anomalies agree with the observed relationships. The model must generate periods of reduced precipitation for the right reasons.

## Description of the Research

Our research was divided into two stages. In the first stage, we determined how clouds over the Prairies differ between wet and dry conditions, as characterized by the Standard Precipitation Index (SPI), on a monthly time scale and a 1° x 1° spatial scale over the 1984-2004 period. We were interested in cloud amount, cloud thickness, cloud amount by layer, cloud optical thickness, and top-of-the-atmosphere (TOA) albedo. We also used the SPI to characterize the 1999-2004 period of the Prairie drought in terms of the frequency and number of consecutive drought months. We compared cloud properties in regions that experienced severe drought to those of clouds formed during non-drought conditions. In the second stage, we compared cloud properties, precipitation, and TOA albedo from the Canadian Regional Climate Model (CRCM) with results from the first stage.

We used observational data from two sources: the Canadian Grid (CANGRID), a gridded precipitation dataset based on surface observations, and satellite data that were assembled for the National Aeronautics and Space Administration Global Energy and Water Cycle Experiment Surface Radiation Budget (SRB) project. The study focuses on the domain 49°–60°N and 240°–265°E. The CANGRID data were used to calculate the SPI, which was then grouped into five classes. They ranged from Severe Drought to Severe Wet. The SRB data provided the cloud and radiation properties for various time scales and averaged over various domains. Analyses were conducted on a spatial scale covering the whole domain and on sub-regions on the basis of surface characteristics and surface data coverage.

Focusing on the drought from September 1999 to December 2004, the number of drought months (SPI less than or equal to -0.5) was calculated for each grid point. This allowed us to identify the structure of the recent drought as well as the locations that experienced particularly high occurrences of drought months. The same procedure was applied to severely dry months and the number of dry months occurring during each season. Using the SPI, we also found the maximum number of consecutive drought months for each grid point. This allowed us to investigate the potential feedbacks that may be responsible for prolonging drought. The maximum number of consecutive drought months was calculated using the SPI for all months of the year, but warm season drought is of primary interest as it is expected to be more susceptible to feedbacks.

Cloud properties were averaged for a variety of circumstances. Different landscapes, for example, can influence the amount and type of cloud cover a region may experience. In addition

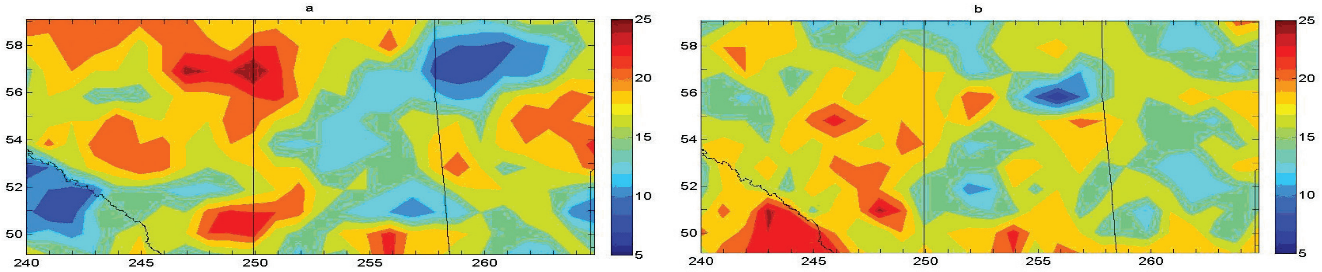


**Figure 1**. Number of months that experienced mild to moderate drought (-1.5 < SPI < -0.5) for the Prairie Provinces from September 1999 to December 2004. a) CANGRID b) CRCM.

to studying cloud characteristics over the long-term, we also examined the cloud properties' behaviour during the 1999-2004 drought. Furthermore, because of issues related to satellites identifying clouds over snow, the study focuses primarily on the warm season (May to September). Monthly mean cloud amount was averaged over the satellite record (1984-2004) for each grid point for four seasons. This emphasized the natural spatial variability of cloud cover for various times of the year. We also computed monthly averages over the satellite record and classified the entire study region according to the five moisture categories. Variability over such a large area allows us to estimate and examine typical values of monthly cloud cover in dry and wet conditions. Mean cloud amounts over boreal forest and agricultural land were averaged for each of the five moisture categories over the warm season from 1984 to 2004.

## Summary of Findings

The CRCM does a good job of predicting average annual precipitation over the Prairies. The data and model placed annual mean precipitation for the period of 1961 to 2004 at 48.6 cm and 47.9 cm, respectively, but the values of annual precipitation in individual years are only weakly correlated. Similar good agreement between model and observations was obtained for mean summer and winter precipitation. The model also accurately reproduces the average annual cycle of precipitation in the southern portion of the Prairie Provinces, where data coverage is much denser than in the north or in the mountains.

The model reproduced the observed geographical distribution of the frequency of dry months for the 1999-2004 drought period, with maxima in eastern and central Alberta and a secondary maximum in southern Saskatchewan (Figure 1), although the model's peak frequencies are less than the recorded observations. The model's summer cloud amounts for 1984 to 2004 are approximately 10% less than those observed in the southern Prairies, but the agreement is better in the northern Prairies and the Rockies.

The average monthly cloud amount anomaly on a 1° x 1° scale classified by the SPI for each grid square for 1984 to 2004 is shown in Figure 2. The average cloud cover anomaly almost always decreases as drought severity increases, except during the winter months (January to March). It is likely that this inconsistency is due to the unreliable retrievals of cloud amounts over snow. The 1999-2004 period of drought revealed a similar trend. If the anomalies for mean cloud amount are averaged over the warm season (May to September) for this period, the mean cloud amount during severe drought is approximately 7% lower than the mean cloud amount during severely wet conditions.

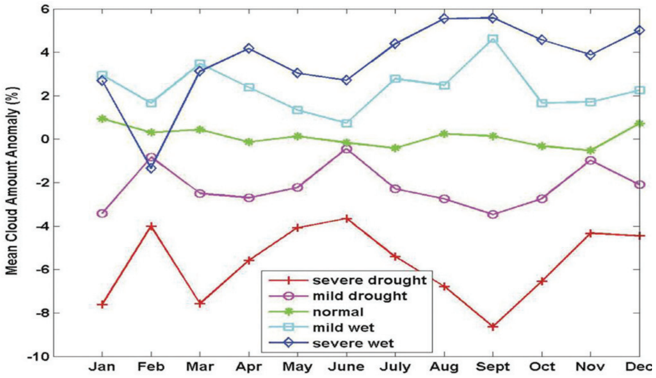


**Figure 2**. Averaged monthly mean cloud amount anomaly (%) over the Prairie Provinces from 1984 to 2004.

Although there is a general increase in mean cloud amount anomaly from negative to positive values with increasing SPI, it should be noted that there is large variability and that the correlation is weak. Stronger correlations are present when albedo anomaly is correlated with SPI because albedo is deduced more directly from the satellite measurements and avoids errors in the estimation of cloud amount. Simulations with the CRCM showed similar results, but the monthly mean cloud anomaly was significantly more sensitive to SPI than the observed amounts.

## Implications

Models such as the CRCM will be a prime tool for understanding and predicting future droughts in a changing climate. These and other models must correctly reproduce each of the physical links leading to reduced precipitation if we are to have confidence in their predictions. Clouds are a key component of the chain; studies like ours, which provide observed relationships between cloud amount and cloud albedo with precipitation anomaly, offer useful constraints on the models.

*Atmospheric Sciences*

# PRECIPITATION EVENTS DURING THE RECENT DROUGHT

*Ronald Stewart, William Henson, Hannah Carmichael, John Hanesiak, and Kit Szeto*

*Ronald Stewart is a Professor and Head of the Department of Environment and Geography at the University of Manitoba. For an extended biography, please see "A Drought Research Initiative for the Canadian Prairies", page 5.*

## Introduction

The climate system is characterized by extremes in the hydrological cycle. Instances of drought and catastrophic precipitation are inherent manifestations of this. Though drought is of course characterized by a general persistence of dryness in a region, it is a dynamic system. Even within a long period of overall dryness, severe precipitation events can occur. The reality is that these two types of extremes, dry and wet, can occur in close proximity.

For a storm to occur during a drought, its development must be sufficiently strong to be able to overcome the dry conditions. It is common for storms to occur during droughts, but often precipitation falls through the dry air near the surface and evaporates (Roberts et al., 2006). Therefore, when a storm occurs during a drought that produces precipitation at the surface, it generally produces more precipitation aloft than it would under normal conditions. On the other hand, drought also tends to exist under high-pressure systems with weak winds in the lower atmosphere. Storms occurring under these conditions tend to be slow-moving since the winds are weak over considerable depths of the atmosphere. Storms also tend to be more vertical, as opposed to being tilted, and therefore more efficient at converting the limited water vapour into precipitation since they do not produce large high-elevation anvils that allow precipitation to fall into dry air far above the surface and sublimate or evaporate aloft. There are therefore competing factors regarding the development of storms and precipitation during drought.

This certainly applies to the recent 1999-2005 drought over the Canadian Prairies. For example, Hunter at al. (2002) documented a major rainstorm over Vanguard, Saskatchewan, which occurred during the 1999-2005 drought. The meteorological drought largely ended for much of the Prairies with a catastrophic event in June 2005. This article focuses on storm events associated with the 1999-2005 drought. The article's objective is to give a brief description of the occurrence and understanding of some of the heavy precipitation events associated with drought.

## Occurence of Storms

First, we examined the frequency of major events during the drought and compared this information to longer-term historical data. To address this, 39 years' worth of climatological data from 13 weather stations across the Prairies were compared with the information gathered over the course of the seven years associated with the drought. An event was included as an extreme precipitation event if the accumulated precipitation recorded for the event was greater than the average monthly precipitation at the station in the month of its occurrence.

Over the seven-year drought period, 39 extreme precipitation events occurred at the stations, giving an average annual occurrence of 5.6 extremes per year. The severity of events ranged from just over 100% to 245% of the average monthly precipitation. The mean severity was 145%. The occurrence of extremes of varying severity decreases exponentially as the severity of the extreme increases, with 62% of extreme events having a severity of less than 150%. The amount of accumulated precipitation for these events ranged from 21 mm to 147 mm, with a mean value of 52 mm. The event with the largest accumulated precipitation occurred in Lethbridge, Alberta, between June 8 and June 10, 2002. The duration of these events ranged from eight hours to 86 hours; the mean duration was 42 hours. An event during the drought can be short-lived with high precipitation rates, or it can be long-lived with low precipitation rates.

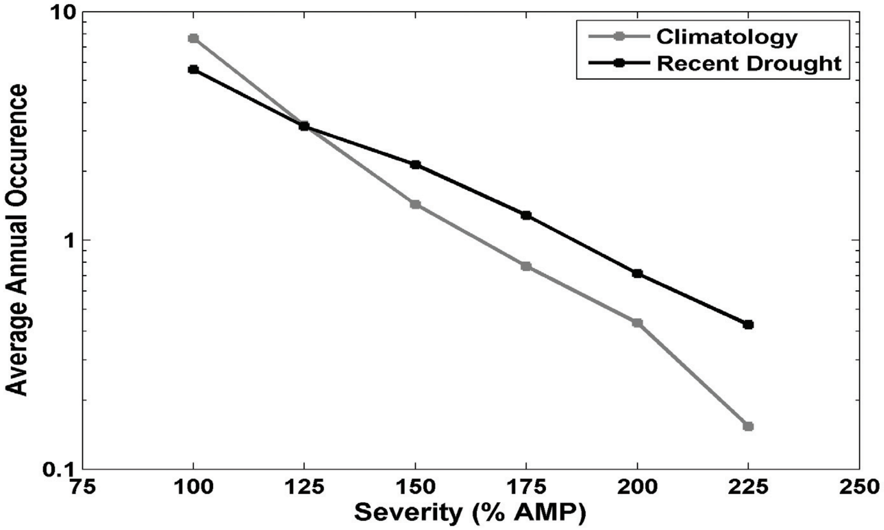


**Figure 1**. Average annual occurrence of extreme events as a function of the severity of the extreme, shown for the recent drought and the background climatology. Each point shows the average annual occurrence of extremes with severity equal to or larger than that of the indicated average monthly precipitation (AMP).

These values were then compared to the longer-term climatology (Figure 1). The annual occurrence of extremes was slightly less during the drought (5.6 extremes per year) than the longer-term record (7.7 extremes per year). There was no statistically significant difference in the mean severity of events between the drought period and the long-term climatology. The maximum severity for an event during the drought was 243% of the average monthly precipitation, but there were three extremes in the long-term climatology that were above 300%. Overall, such information confirms the presence of major events during drought. It also shows that, by at least one measure of precipitation at the surface, there was relatively little difference from long-term climatology.

## Convective and Stratiform Precipitation

Another issue to address is whether precipitation events during the drought were convective. Major convective storms generally produce lightning. To address this issue, all summer rain events producing at least 10 mm of precipitation over the course of 24 hours within the boundaries of the Canadian Prairie Provinces during the recent drought were recorded. Raddatz and Hanesiak (2008) found that most of the nearly 1000 events (79%) were solely or partially convective (lightning was recorded during the event). In June 2002, 74% of the events were solely or partially convective; in July 2002, 85% of the events were convective; in August 2002, 79% of events were convective; in June 2002, 84% of the rain area was from events that were solely or partially convective; in July 2002, 93% of the rain area was solely or partially convective; in August 2002, 86% of the rain area was solely or partially convective. It must be noted that some events, although not as common, produced heavy precipitation without lightning.

For significant rain events with convection, the most frequent forcing mechanisms were mesoscale (local and regional) processes including daytime heating (28%), surface low-pressure centres (16%), surface troughs (14%), and warm and cold fronts (both 14%). While mesoscale mechanisms were responsible for 28% of the significant rain events with convection, they generated just 11% of the rain area with convection. Surface low-pressure centres, responsible for just 16% of the events with convection, produced 25% of the rain area with convection.

The most frequent forcing mechanisms for significant rain events without convection were surface low-pressure centres (25%), surface troughs (22%), cold fronts (19%), and cold lows (12%). Such systems are often linked with more gently rising air. The precipitation from these would be referred to as stratiform precipitation. Such events give rise to less intense rainfall rates but they often last a long time.

## Storms in Relation to Surface Features

The Earth's surface and its vegetation play a major role in deep convective storm development, mainly through evapotranspiration, which supplies moisture to the atmosphere. Storms need moisture to develop. It is important to determine whether storms during the recent drought were significantly affected by the varying surface conditions. To do this, vegetation growth and cloud-to-ground lightning activity were examined for the summers of 1999-2005 for the entire cropped grassland region of the Prairies (Figure 2). As expected, wet areas, with greater evapotranspiration generally had greater lightning activity than dry areas. During 2000 to 2002, when the drought was most intense and widespread, lightning was reduced. In contrast, the years 1999 and 2003 to 2005, which did not have as large of a dry region, showed little deviation from climatology in terms of lightning frequency.

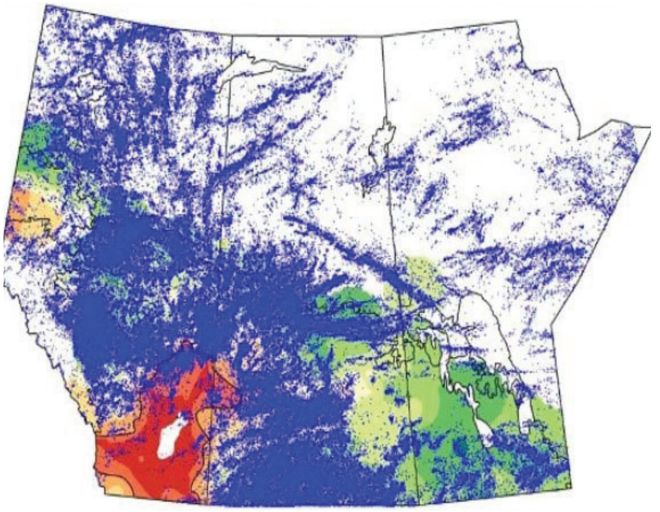


**Figure 2**. July 2000 lightning strikes (blue dots) and the amount of water in the root-zone for crops expressed as a percentage of the soil's capacity to hold water. Deep red and green shades represent percentages of holding capacities less than 30% (dry) and greater than 60% (wet), respectively.

The spatial distribution and size of wet and dry areas appear to play a role in determining the strength of their respective relationships with lightning anomalies. The months and years with larger contiguous wet and dry areas showed the strongest relations between soil moisture and lighting. If a patch is too small, the overall impacts will be minimal.

## A Storm of Mammoth Proportions

As mentioned earlier, an extreme precipitation event occurred in June 2002 (Figure 3). From June 8 to 11, 2002, extreme precipitation was produced near the Canada-U.S. border, causing major flooding over southern areas across the Prairies. This flooding was preceded by a serious and damaging drought. The Canadian Dam Association estimated the return period of such a rainfall event to be 258 years if the event is included in the background climatology and 1,486 years if it is not.

Similar to most other major rainstorms occuring on the Prairies, moisture from the Gulf of Mexico and the southern United States provided the main source of moisture that fuelled the system. Also similar to the other systems, a surface low-pressure system over the mid-western United States transported a large amount of moisture into the eastern Prairies. There was a near-steady surface front near the international border that forced air to rise in this vicinity. This led to very heavy convective rain over the eastern Prairies. Excess moisture was transported by the low-pressure system toward the western Prairies and into the foothills of the Rockies to produce long-lasting heavy orographic rainfall over the western Prairies.

The longevity and severity of the system was a result of complex interactions between the storm processes that took place in the background drought conditions and the Prairies' physical environment. The persistent high-pressure area that was affecting much of mid-western Canada at the time was also partly responsible for the Prairie drought. This synoptic situation and the intense atmospheric cooling induced by rainfall evaporation in the dry air over the Prairies acted together to accentuate the north-south pressure difference near the international border between the low-pressure centre to the south and the high-pressure centre to the north. This strengthening of the pressure gradient enhanced the easterly winds in this region (maximum winds in a low-level jet located one kilometre above the surface). The low-level jet greatly facilitated the transport of moisture from the eastern Prairies into the western Prairies and produced a tremendous amount of rainfall when the strong low-level flow reached the foothills in Alberta. In addition, strong atmospheric heating due to the conversion of large amounts of water vapour into precipitation near the foothills of Alberta in turn led to an even more intense low-pressure system. The intensified low-pressure centre drew warmer, moister air from the south.

The interaction between the storm processes and the background drought conditions within the Prairies' physical environment allowed for mutual amplification of the storm features and the phase-locking of the system to the Rockies, resulting in slow system propagation and long-lasting extreme precipitation over both the eastern and western Prairies. While the background drought played a significant role in the development of the extreme event, the ample amount of rainfall from the system, particularly the rain that fell over those western regions in which the drought was most severe, also alleviated the impacts from the severe drought in the region for an extended period.

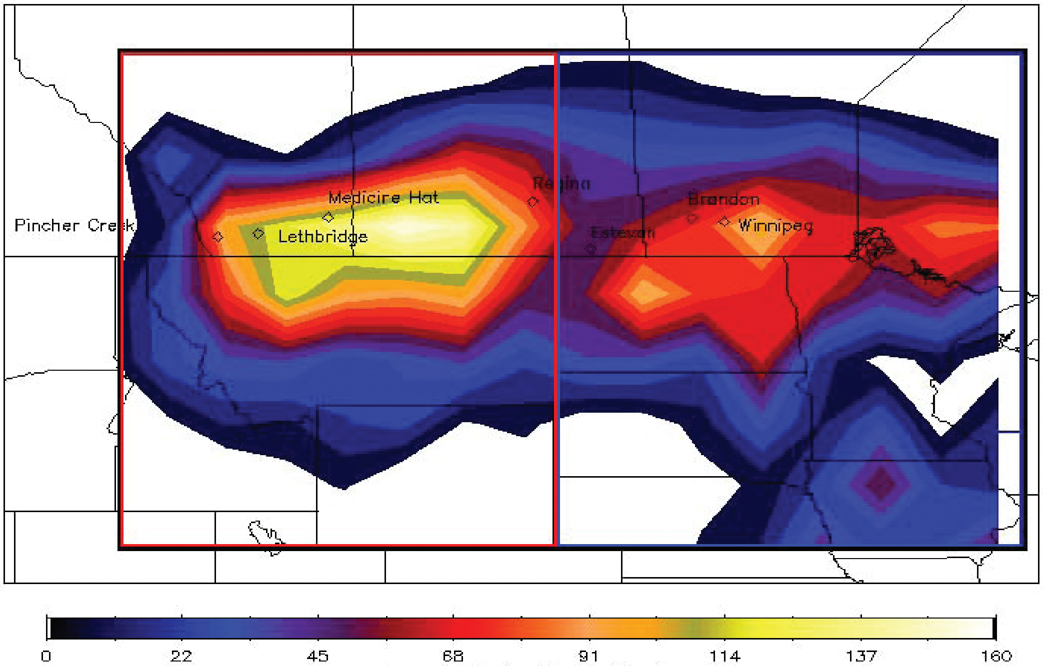


**Figure 3.** Distribution of accumulated precipitation from the Canadian Meteorological Centre Global Environmental Multiscale model Analysis for the period June 8, 2002 to June 12, 2002.

## Winter Storms

Most of the attention devoted to storms has focused on summer events. For cold climate droughts such as those that occur over the Canadian Prairies, winter events are also important. The ground is frozen and provides little direct moisture input to feed the storms. Moisture must be advected into the Prairies from other regions. This also means that the dryness of the surface does not significantly affect the locations of ensuing precipitation.

Come spring, melting snow quickly creates a wet surface. The pattern of dryness and wetness over the Prairies is then altered. The pattern created over the course of the previous summer is supplemented by the pattern that developed as a result of winter precipitation. This altered pattern in turn affects the surface feedback locations referred to earlier.

Although the winter storms mainly produce snow, surface temperatures sometimes approach or occasionally exceed 0°C. In such cases, rain and/or freezing precipitation can occur. During the recent drought, freezing rain occurred every winter over the Prairies. The ice that blankets the snow maintains the snow pack by preventing loss (from blowing snow, for example). Winter events then can have a major impact on water storage.

## Summary and Concluding Remarks

Extreme precipitation events during the summer and winter were not uncommon during the 1999-2005 drought. Their overall occurrence was slightly less than expected from climatology but, by at least one measure, they were at least as severe.

There is more than one mechanism at work to create these extreme events. Some were mostly convective, while others were not. Such variability translates into variations in precipitation intensity. Events with convective activity generally lead to heavy precipitation rates for short durations; stratiform events lead to the reverse. Even if the total amount of precipitation is consistent, the variation in rate can lead to major differences in surface impacts. Variations in rate, for example, affect the proportion of water that runs off instead of infiltrating the soil. There is evidence that such findings are not just related to the most recent drought. Major storms, including tornadoes, occurred during the catastrophic 1930s drought over the Prairies. Disastrous storms associated with or occurring at the end of droughts have been observed in other regions of the world, including the United States and Australia. Addressing drought can therefore also involve the study of storms. These two ends of the spectrum of extreme conditions can occur in close proximity or simultaneously and interact with each other.

It is imperative that we understand this high degree of variability in the climate system, including dry and wet regimes. With generally rising temperatures, such flip-flops may become more common as the hydrologic cycle speeds up, including the factors leading to its extremes.

*Atmospheric Sciences*

# LAND COVER AND OROGRAPHIC AND CONVECTIVE STORM LINKS TO ALBERTA DROUGHT CONDITIONS

*Geoff Strong*

*Geoff's training includes a Ph.D. in Meteorology from the University of Alberta (1986) and one year of intensive training for operational forecasting from the Environment Canada Meteorological Service (1967). His 45-year career includes experience across seven provinces includes teaching at the high school level, forecasting, and researching atmospheric sciences with the Alberta Research Council Hail Project and Environment Canada. He has extensive field research experience in Alberta, Saskatchewan, and the Northwest Territories, focusing on thunderstorms, evapotranspiration, atmospheric water budgets, and drought. He also participated in field research projects in Oklahoma (1979), Montana (1981), and Greece (1986). Forecasting experience continues to influence his research goals, and he has a long-standing passion for Alberta thunderstorms and their effect on precipitation extremes and drought. Retired from Environment Canada in 1998, Geoff continues freelance research in these areas from his home near Edmonton. As Adjunct Professor at the University of Alberta and The King's University College in Edmonton, he has supervised several graduate students and teaches sessional courses that help fund his field research efforts while continuing to participate in research networks such as Alberta GPS Atmospheric Moisture Evaluation and DRI. Geoff is also a staunch public defender of climate science, writing newspaper and Canadian Meteorological and Oceanographic Society Bulletin articles, giving public talks and occasional radio interviews.*

## Motivation and Background Research

This research evolved from investigations carried out by the author on thunderstorm genesis over the Alberta foothills and their dependence on local moisture sources, including evapotranspiration from grain crops (Strong, 1986; Strong and Smith, 2001), evapotranspiration (ET) and moisture budgets in Saskatchewan, and the influence on local convective storms (Hyrnkiw and Strong, 1992; Strong, 1997). A subsequent climatological study on Prairie temperature and moisture cycles suggested possible physical links between thunderstorms and drought, hence this participation in DRI.

It is also known that 50% of Prairie precipitation occurs during the summer months, virtually all of which involve convective clouds and storms. We see a complex and mutual interdependence between Prairie convective clouds, precipitation, soil moisture, and crop growth. Each of these factors, moreover, interacts with periods of drought. The synthesis provided here then necessarily involves results from the above studies carried out by the author, including some reanalysis of previous data to focus on drought.

## DRI Research Description

The DRI research and reanalysis of the studies reported here are incorporated within four closely related topics.

### Thunderstorm Dynamics and Local Moisture Sources

Ongoing research on mountain wave-induced drylines related to thunderstorm initiation over the Alberta foothills was initially carried out independent of DRI research. It was previously known that local daily ET, especially from grain crops, was an important source of moisture for thunderstorm initiation over the foothills, with moisture converging over the foothills due to lee cyclogenesis beneath a capping lid initially formed from large-scale and orographic subsidence. Reanalysis of the Pine Lake tornado storm of July 14, 2000, thought to have been initiated by a dryline, suggested some similarities in dynamics between the dryline and dry air over a severely drought-stricken area to the south-east. The storm moved eastward through the northern periphery of the drought area just south of Red Deer, Alberta. Rather than weakening in the vicinity of dry air, it intensified, resulting in the killer tornado. This suggests a possible link between dryline-initiated storms and drought areas. An investigation of comparative processes followed.

### Background Temperature/Moisture Cycles and Trends

A climatological study of Prairie surface temperatures and moisture at major sites in Alberta, Saskatchewan, and Manitoba had been carried out under contract to Alberta Environment.

This study was undertaken to determine average climate background values and to note any persistent cycles or trends that may be related to centres of storm development and extremes of precipitation or drought. This preliminary study was completed as DRI was initiated and was the starting point for the author's drought research. It provides valuable background information for the study of thunderstorm dynamics and local moisture sources. An effort to find similar trends in upper air data is incomplete at this stage.

### Evapotranspiration from Grain Crops

A key variable in drought is soil moisture (or lack thereof) and plants' ability to survive with reduced moisture for the photosynthesis process. Plants must also transpire moisture to the atmosphere as an important cooling mechanism, especially during high temperature events such as those often experienced during drought. This transpiration from plants, especially grain crops that have high rates of ET because of their shallow root zones, also happens to be a critical diurnal source of moisture for convective cloud and thunderstorm development. When shallow moisture disappears during the early stages of drought, grain and vegetable crops are the first plants to suffer. Convective clouds are also negatively affected, which further exacerbates the root-zone moisture supply through reduced summer precipitation, a positive feedback with a negative impact on crops. Moisture budget analyses for the Regional Evaporation Study of 1991 in Saskatchewan provided daily evapotranspiration estimates as high as 12 mm (Strong, 1997), but this study was not designed to distinguish ET rates over different vegetation sources. A simple first attempt to resolve these sources involved a fixed transect of measures across Prairie grass and a wheat crop on a 180-metre baseline at St. Denis, Saskatchewan in 1992, but involved measures at only one level, the standard 1.5-metre height. During 2009, additional sensors were installed at an existing Environment Canada site at Kenaston, Saskatchewan to measure profiles of moisture up to 6 m in elevation above grass and a canola crop, along with existing eddy correlation flux and soil moisture measurements at the same site. For comparison, spot profiles of mixing ratio above canola were measured at four locations in the Edmonton area on single days.

### Rural versus Urban Moisture Fluctuations and Dry Islands

This part of the drought research evolved serendipitously, while carrying out continuing mobile transects in search of the dryline during the Understanding Severe Thunderstorms and Alberta Boundary Layer Experiment (UNSTABLE) project of July 2008 (Taylor et al., 2007). While traversing through small urban centres of 1,000 to 10,000 inhabitants (such as Sundre and Wetaskiwin, Alberta) in agricultural districts, mixing ratios were observed to drop by up to 1 g kg$^{-1}$ below rural background values, resulting in urban dry islands. Furthermore, high-frequency fluctuations of +1 g kg$^{-1}$ resulted from passage alternating between crops, pasture, and lines of trees. These high-frequency fluctuations virtually ceased inside urban boundaries. This prompted mobile transects across the larger urban city of Edmonton (approximate population of 800,000) during 2009, with a corresponding stronger dry island.

## Summary of Findings

A few results from the previous four analysis areas are presented in the context of their contribution to both convective storm and drought research.

### Thunderstorm Dynamics and Local Moisture Sources

Documentation of the Alberta foothills' dryline was made possible during field data collection for the Alberta GPS Atmospheric Moisture Evaluation (AGAME, 2003-2007), using mobile transects of pressure, temperature, and humidity over the foothills. These transects were continued during the 2008 UNSTABLE field programme. Drylines are thought to sometimes increase boundary layer convergence at the rear flank of the moist air underlying capping lids, thereby helping to initiate convective storms. Multiple transects across drylines during UNSTABLE revealed moisture gradients varying from 15 to 50 g kg$^{-1}$ km$^{-1}$, virtual discontinuities in the atmosphere not previously documented in Canada. Reanalysis of the Pine Lake tornado storm of July 14, 2000 strongly suggests a dryline initiation. Subsequently, the storm appeared to have intensified as a result of dry air over drought-stricken south-east Alberta converging with moist air ahead of the storm. This suggests a direct link between drought and storm intensification under certain conditions, while renewed storm outbreak periods are often associated with the cessation of drought.

### Background Temperature/Moisture Cycles and Trends

The climate study on Prairie moisture cycles showed that Alberta surface moisture peaks in late July to early August, with an average peak mixing ratio near 9.5 g kg$^{-1}$, coincident with peaks of crop growth, maturity, and transpiration. Manitoba moisture tends to peak in early July, while Saskatchewan's bi-modal peaks match those of Alberta and Manitoba. Climatic cycles in mixing ratio occurred with an average period of 12 days throughout the Prairies, which is very close to the cycle period for storm outbreaks in Alberta (Strong and Smith, 2001). These similar cycles are likely linked to the frequency of synoptic-scale shortwave systems that migrate across the Prairies (Strong, 1979). When soil moisture is low during drought conditions, evapotranspiration and the amplitude and frequency of moisture cycling diminish, as do convective storm outbreaks. There is some evidence to suggest that drought conditions are initiated when moisture cycles diminish significantly and are sometimes terminated with the return of a thunderstorm outbreak.

## Evapotranspiration from Grain Crops

Maturing grain crops contribute significantly to the moisture budget of Prairie convective storms (Strong, 1986, 1997; Raddatz, 2000). Daily summertime evapotranspiration rates have been shown to exceed 10 mm under high soil moisture conditions in agricultural regions (Strong, 1997), and crops such as canola, barley, wheat, and oats are large contributors to this. The 1992 St. Denis transect data show that during July and August 1992, the daily average (18 days) background moisture mass (mixing ratio) at St. Denis, Saskatchewan increased by 50%, from 8 to 12 g kg$^{-1}$ (Figure 1). At the same time, average mixing ratios at the standard 2 m height were consistently more than 1 g kg$^{-1}$ higher over wheat than over Prairie grass just 180 m away. For both vegetation types, transpiration peaked shortly after noon local time (after 1800 UTC). Since advective components of moisture are averaged to near-zero in 18 days (Strong, 1997), one can infer from Figure 1 that the average ET was 4 mm (some days may have been under 1 mm, others near 10 mm), and that the wheat transpired at least 1 mm more than grass during this period.

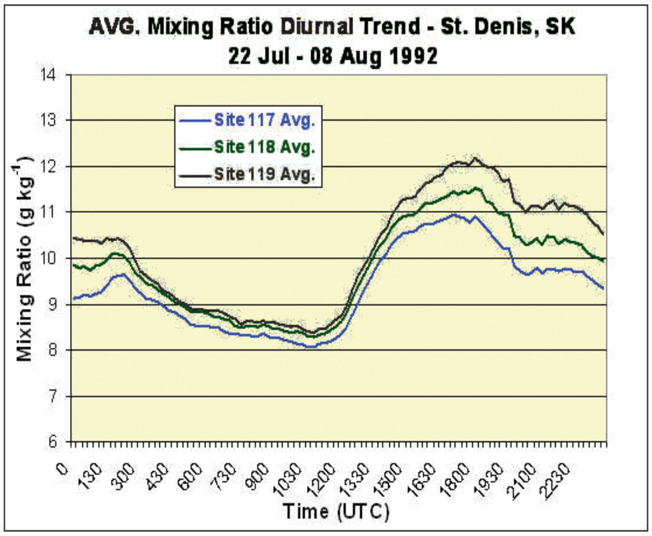


**Figure 1**. 18-day average diurnal cycle of mixing ratio over wheat (site 119), transition zone (site 118), and grass (site 117) on a 180-metre fixed transect at St. Denis, Saskatchewan, July 22 - August 8, 1992.

The St. Denis experiment was carried out with a minimum of instrumentation and lacked any vertical profiles of moisture. The importance of the results only became clear when mobile transects were carried out during recent thunderstorm and drought studies. Consequently, the St. Denis experiment was reproduced in 2009 at Kenaston, Saskatchewan, but with vertical profiles over both crop (canola) and grass sites, along with existing eddy correlation flux data and soil moisture measurements. In addition, spot vertical profiles of mixing ratio above canola crops were recorded at four different locations on single days within 20 km north-east and south-west of Edmonton, AB during 2009. These will provide an independent Alberta dataset to compare with the more detailed Kenaston data now being processed. Results from the four Alberta moisture profiles over canola are summarized in Figure 2, showing five-minute average values of mixing ratio at 30 cm, 50 cm, 100 cm, 150 cm, 200 cm, 250 cm, and 300 cm above ground, with data output at 15-second intervals (for approximately 20 values at each level).

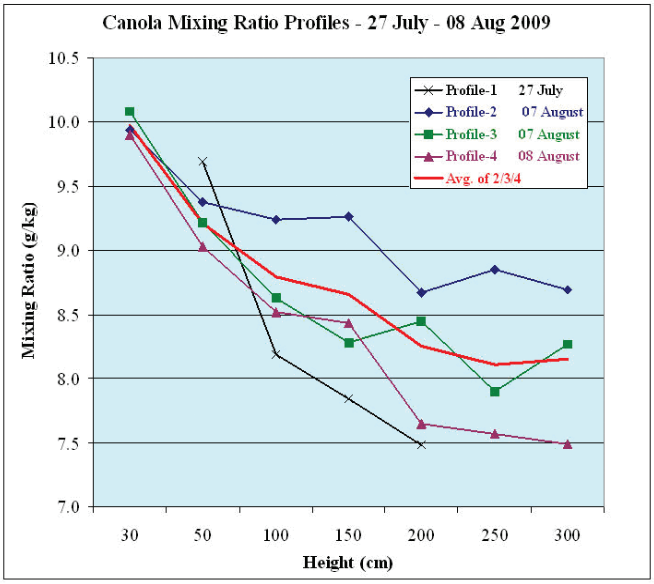


**Figure 2**. (a) Sensors at 30-cm and 300-cm levels on August 8, 2009, and (b) averaged mixing ratio profiles above canola at four different locations near the Edmonton area, July 27 – August 8, 2009.

The top of the canola canopy varied between 50 cm and 100 cm in each case, and all profiles were carried out between 11:40 MDT and 14:10 MDT; that is, after initial convective mixing had taken place but still during the peak transpiration period. Detailed ambient values of mixing ratio for the region around these sites varied from 6.5 g kg$^{-1}$ (July 27, 2009) to 8.5 g kg$^{-1}$ (August 8, 2009). These four brief profiles give a clear indication of a marked vertical gradient of mixing ratio of 2 g kg$^{-1}$, mostly in the lowest 2 m above ground. This can be attributed directly to transpiration from the canola and surrounding vegetation, and corroborates the 1992 St. Denis data. The Kenaston data will undoubtedly shed more light on this.

## Rural versus Urban Moisture Fluctuations and Urban Dry Islands

As noted earlier, while carrying out the mobile transects for drylines during UNSTABLE, the gradient of moisture between grassland and cropped areas noted above was detected in mixing ratio data while driving from rural agricultural areas into small urban landscapes. The gradient was even detectable while passing lines of trees or grazing land within rural agricultural areas. Figure 3 gives an example for the town of Wetaskiwin (pop. 11,000) on July 12, 2008.

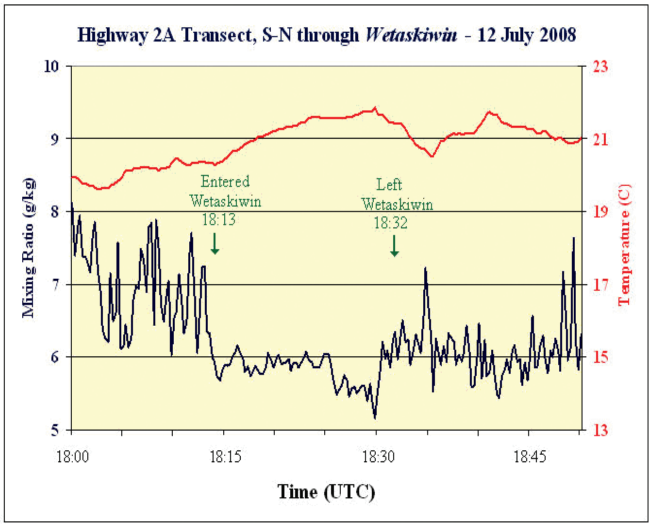


**Figure 3**. Mobile mixing ratio and temperature trends exhibiting urban dry island effect caused by a drop in local evapotranspiration moisture source when traversing small urban centres within agricultural districts.

Upon entering urban centres such as this one, the cycling of mixing ratio caused by fluctuations between crops and other vegetation was almost eliminated, while the average mixing ratio dropped by about 1 g kg$^{-1}$, in this case from 7 g kg$^{-1}$ to under 6 g kg$^{-1}$, revealing a small urban dry island effect. The temperature trend, though less variable, gives a hint of a small urban heat island as well (approximately 0.5 °C after considering daytime heating). The dry island effect is perhaps more significant when one considers that this whole area had been under drought conditions. Subsequent transects across the much larger Edmonton urban environment during 2009 reveal a corresponding stronger urban dry island of at least 3 g kg$^{-1}$, as well as the anticipated urban heat island.

The urban dry island results have important implications for convective storm intensity as storms approach larger urban centres where a dry island may exist and possibly for the maintenance of drought conditions. Preliminary analyses suggest a summertime rain shadow downwind from Edmonton, possibly resulting from either storms dissipating over the city due to depleted moisture, or propagating on a new track towards a new moisture source south-east or north-east of the city.

## Implications

Figures 1 to 3 emphasize the importance of local ET sources, particularly grain crops, on the Prairies. This has critical implications for the initiation and cessation of drought, as well as for the production of convective storms, the latter being responsible for redistributing moisture across the Prairies. Work is proceeding on completing the analysis of Edmonton transects from more than 20 days, as well as data from the four vertical profile sites where mixing ratio data of up to 3 m were collected over canola crops. It is anticipated that examination of storm tracks from archived Carvel radar images would shed more light on the dry island/rain shadow hypothesis. If verifiable, this would help explain the maintenance of the 1999-2004 drought east of Edmonton into early 2010.

In addition, more detailed fixed profiles over both barley crops and pasture were collected at Kenaston, Saskatchewan throughout the summer of 2009, along with eddy correlation and soil moisture data. These additional data will provide quantitative estimates of evapotranspiration and, together with the mobile transects, will provide a means to quantify the effect of crop evapotranspiration on convective clouds and precipitation. Preliminary analysis of Kenaston data concur with the Edmonton results summarized in Figure 2.

## Acknowledgements

Others have contributed to this research with instrumentation and data collection, most notably Craig Smith (Environment Canada, Saskatoon) and Danny Brown (M.Sc. student, University of Alberta).

*Atmospheric Sciences*

# VALIDATION OF MODELLED SOIL MOISTURE AND EVAPOTRANSPIRATION FROM THE PAMII MODEL, AND AN ASSESSMENT OF THEIR UTILITY FOR TRACKING DROUGHT

*Julian Brimelow and John Hanesiak*

*Julian is currently a Ph.D. candidate in the Department of Environment and Geography at the University of Manitoba. Under the guidance of his supervisor, Dr. John Hanesiak, Julian is investigating linkages between soil moisture (and vegetation health) and thunderstorm activity on the Canadian Prairies. Their work, conducted under the auspices Drought Research Initiative, is intended to improve our understanding of mechanisms that may exacerbate or perpetuate drought. Julian graduated from the University of Pretoria (South Africa) with a B.Sc. in Meteorology in 1993 and completed his M.Sc. at the University of Alberta in 1999. Julian has worked as a meteorologist for the South African Weather Service and the British Antarctic Survey and as a research assistant at the University of Alberta.*

## Background

Soil moisture content and vegetation are two critical and closely related components of the land surface that are heterogeneous in both space and time (Kim and Wang, 2005). During the growing season, precipitation and evaporative demand modulate soil moisture content and vegetation health, which in turn affect the surface moisture flux into the atmospheric boundary layer and the regional hydrologic cycle.

Field crops (wheat, canola, and barley) cover about 60% of the grassland eco-climate zone of the Canadian Prairies. Spring wheat alone accounts for about 50% of the cropped area (Hanesiak et al., 2009). Given the importance of evapotranspiration (ET) from crops and grasslands for convective processes and the overall water budget of the Canadian Prairies, a part of Canada far removed from oceanic moisture sources, it is crucially important that we accurately simulate the intra- and inter-seasonal variability in ET.

Because precipitation tends to be highly variable in both space and time, it is expected that the root-zone soil moisture fields will typically be heterogeneous at any given time across the agriculture zone of the Prairies. In the absence of a high spatial resolution *in situ* soil moisture monitoring network on the Canadian Prairies, one has to rely on alternative methods for tracking soil moisture and ET. Surface vegetation-atmosphere transfer models are often used to map the continually evolving spatial distribution of soil moisture and ET in response to atmospheric drivers. Here, we use the second-generation Prairie Agrometeorological Model (PAMII) of Raddatz (1993). PAMII is like other models such as the Variable Infiltration Capacity model (Liang et al., 1994) and the Decision Support System for Agrotechnology Transfer (Ritchie and Otter, 1985), which are routinely used to simulate soil moisture and ET. PAMII simulates the evolution of root-zone soil moisture content (top 1.2 m) and vegetation using a daily time step. Unlike other models, which are commonly used to model ET (e.g., Granger and Gray, 1989), PAMII does not explicitly take into account the surface energy balance. ET in PAMII is governed by photoperiod, vapour pressure deficit, leaf fraction, aerodynamic resistance, and canopy resistance. Input data consist of daily observations of minimum and maximum temperature and rainfall and prognostic vapour deficit from the regional Canadian Global Environmental Multiscale model.

While PAMII has been used extensively by the agriculture and research community in Canada (e.g., Hanesiak et al., 2009), its ability to simulate the evolution of the root-zone soil moisture and ET has yet to be verified against a comprehensive set of *in situ* observations. Here we will demonstrate that the PAMII model is a useful tool for modelling soil moisture and ET and that PAMII can be used to track agricultural drought.

## Validation of Soil Moisture Simulations

Brimelow et al. (2010b) validated PAMII against *in situ* soil moisture observations from three sites (with contrasting soil texture) on the Canadian Prairies in 2004 and 2005. They also quantified the sensitivity of modelled root-zone soil moisture and ET to uncertainties arising from the specified soil water retention properties. They found that PAMII showed significant skill in simulating the evolution of root-zone soil moisture content during the growing season. PAMII also captured the salient features of the soil moisture content at each site. Specifically, correlation coefficients of determination ($R^2$) between simulated and observed root-zone soil moisture content were between 0.65 and 0.90, while the mean absolute errors were typically less than 10% of the mean soil moisture content. In light of these findings, Brimelow et al. (2010b) concluded that PAMII can be used successfully as a diagnostic tool to track the evolution of root-zone soil moisture content. They noted, however, that correct modelling of soil moisture content is contingent on accurately identifying the site-specific permanent wilting point and field capacity. They suggested using multiple pedotransfer functions to quantify the uncertainty in simulating soil moisture associated with errors in the soil texture and associated soil hydraulic properties.

## Validation of ET Estimates

Brimelow et al. (2010c) validated modelled daytime ET estimates from PAMII against daytime ET estimates from eddy covariance systems at West Nose Creek (a barley field located north-west of Calgary, Alberta) and a FluxNet site (short-grass Prairie located west of Lethbridge, Alberta). In addition, the model's performance was validated for contrasting growing seasons at the grassland site.

At the barley site, the model explained about 50% of the observed variance in ET for the 22 days considered here. PAMII displayed a systematic negative bias of between -0.7 mm $d^{-1}$ and -1.3 mm $d^{-1}$ (17% to 24% relative error) over the cereal crop, depending on the reference value specified for the minimum stomatal resistance (rs_min). Mean absolute and root mean square errors (RMSE) were near 1.0 mm $d^{-1}$. These skill statistics apply only to a barley crop for the second half of the growing season.

PAMII showed skill at modelling the day-to-day and inter-seasonal variability in ET at the grassland site. Specifically, the model explained 70% of the variance in observed ET. Mean absolute errors and mean RMSE errors were less than 1.0 mm $d^{-1}$. The systematic negative bias of approximately -0.30 mm $d^{-1}$ over the grassland represents a relative mean error of 16%. PAMII successfully captured the increase (decrease) in accumulated growing season ET for the wet (dry) growing seasons at the short-grass Prairie site.

Based on optimization of the model runs for each site, new reference values for minimum stomatal resistance for grassland (rs_min = 80 s $m^{-1}$) and cereal crops (rs_min = 50 s $m^{-1}$) were proposed for PAMII. Brimelow et al. (2010c) noted that no single value of minimum reference stomatal resistance worked best for all years at the grassland site and proposed improvements to the canopy resistance module in PAMII.

## PAMII as a Drought-tracking Tool

Brimelow et al. (2010b,c) also compared the performance of PAMII with the skill scores of similar models from around the world and determined that the skill of PAMII is comparable with and even superior to a wide range of models of varying complexity when predicting soil moisture and ET. Thus, one can be confident that PAMII can be used successfully as a diagnostic tool to track the evolution of root-zone soil moisture content and ET.

Figure 1 shows the modelled mean relative root-zone plant available moisture content (PAW) for each month of July between 1999 and 2005. One can see the areas of drought (orange hues) emerging over southern Alberta in 2000. The drought region then expanded northward and eastward into Saskatchewan by July 2001. In July 2002, the area of agricultural drought covered most of Alberta and Saskatchewan, with the driest conditions observed over central Alberta and central Saskatchewan. Conditions improved in central Alberta and central Saskatchewan by July 2003, but southern Alberta and southern Saskatchewan were still experiencing relatively dry root-zone soil moisture conditions. By July 2004, the soil moisture situation improved over all areas, with the exception of south-eastern Alberta. In July 2005, most areas on the Prairies were once again experiencing favourable root-zone soil moisture conditions.

A limitation of calculating the monthly mean PAW (Figure 1) is that this metric does not explain how conditions depart from the long-term mean. In order to create anomaly maps, however, we must have a long-term database. Even then, such anomaly maps do not necessarily provide insight into the cumulative impact of soil moisture stress on vegetation. Lab and field work have shown that incipient moisture stress for most plants begins when PAW approaches 50% (e.g., Shen et al., 2002). Notable loss of photosynthetic activity (Vico and Porporato, 2008) increases in ABA (Abscisic Acid) levels (Schurr et al., 1992), and reduction in biomass growth (Mitchell et al., 2001) occur once the root-zone PAW declines below 30%. Thus, calculating the accumulated number of days during the growing season for which the root-zone PAW is less than 30% might be a useful metric for identifying the intensity and extent of agricultural drought.

Normalized Difference Vegetation Index (NDVI) maps are a useful diagnostic tool for tracking drought (e.g., Ji and Peters,

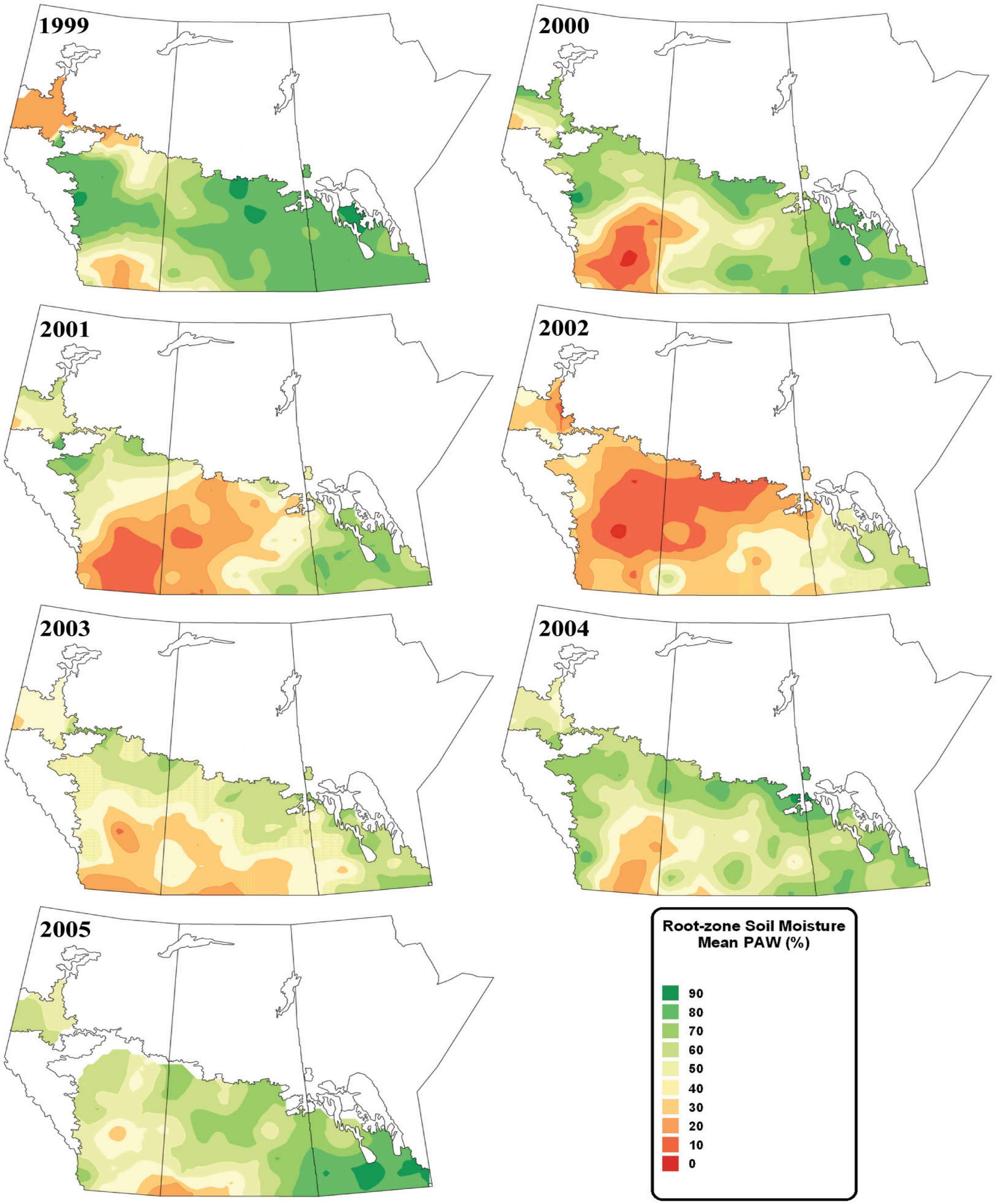


**Figure 1**. Mean modelled monthly relative root-zone relative plant available water (PAW) content from PAMII for 1999 through 2005. PAW is the amount of water in the root-zone for crops (given as the difference between the observed volumetric water content and the wilting point) expressed as a percentage of the soil's capacity to hold water (given as the difference between the field capacity and the permanent wilting point).

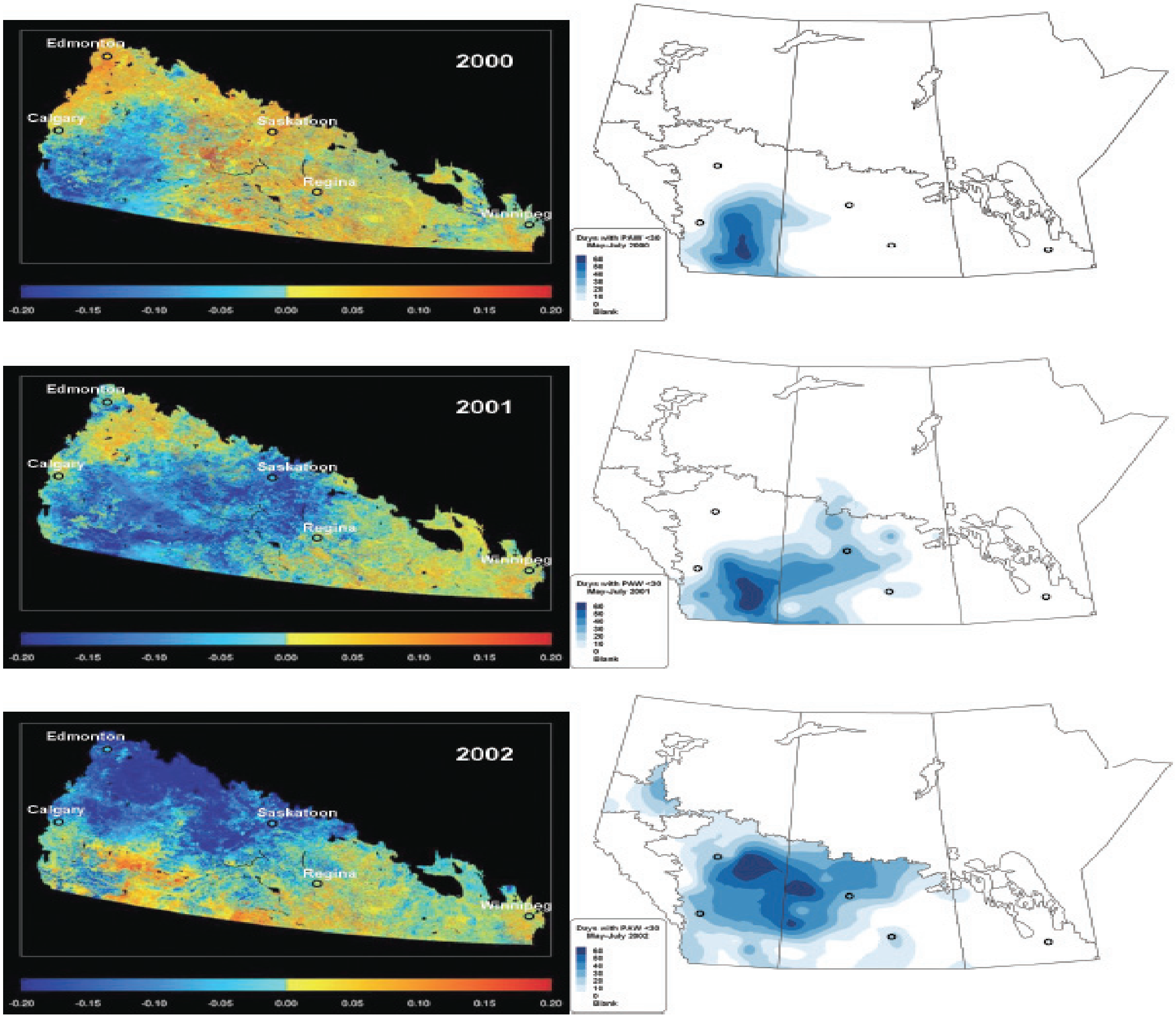


**Figure 2.** Left panel: NDVI anomaly maps for July 11-20, 2000, 2001, and 2002 (courtesy Luo et al., 2008). NDVI anomalies are with respect to the 2000-2008 means. Right panel: Accumulated number of days with root-zone PAW at less than 30% calculated by PAMII between May 1 and July 31 for 2000-2002. Open circles represent locations of major urban centres.

2003) and for providing yield forecasts (e.g., Reichert and Caissy, 2002). Figure 2 compares the NDVI anomalies (for July 11 to 20, 2001-2003) for the Canadian Prairies (Luo et al., 2008) with the (much lower resolution) maps of total number of days with PAW less than 30% between May 1 and July 31, 2000-2003. It is evident from Figure 2 that those areas with a high frequency of severe moisture stress days correspond very closely with those areas shown by the NDVI anomaly maps which have much less dense (i.e., stressed) vegetation than normal.

One limitation of NDVI data is that it typically takes vegetation two to four weeks to respond to anomalies in soil moisture (Adegoke and Carleton, 2002). Thus, the advantage of calculating the accumulated number of days for which PAW is less than 30% is that attention is drawn to those areas in which vegetation is likely to experience significant moisture stress in the coming two to four weeks.

Such maps, if made available in real-time, would be of much use for stakeholders and decision-makers as they prepare for and make decisions in times of drought. Furthermore, they would complement the information on ET and soil moisture that could be provided by the PAMII model.

*Hydrologic Sciences*

# THE USE OF SOIL MOISTURE FROM A MACROSCALE HYDROLOGICAL MODEL TO RECONSTRUCT, MONITOR AND FORECAST DROUGHT CONDITIONS ON THE CANADIAN PRAIRIES

*Charles Lin and Lei Wen*

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## Background and Introduction

Most regions of Canada have frequently experienced droughts in the past and will continue to do so. Droughts are responsible for four of the six most costly natural disasters in modern Canadian history and all four droughts took place within the last 25 years. The Canadian Prairies are particularly susceptible to drought and there was at least one catastrophic drought per century dating from the seventeenth century. The most recent Prairie drought began in 1999 and ended in 2005. This drought peaked during 2001 and 2002 and has been recognized as one of Canada's worst natural disasters. As a result, the Canadian Drought Research Initiative was established in 2005. One of DRI's three major objectives is to assess and reduce uncertainties in the prediction of drought over the Prairies.

A drought is an extended period of abnormally dry weather that is sufficiently prolonged for the lack of water to cause a serious hydrological imbalance in the affected area. According to the World Meteorological Organization (WMO), agricultural drought relates to a shortage of available water for plant growth and is assessed as insufficient soil moisture to replace evapotranspirative losses. Having accurate soil moisture information is thus essential to assessing and predicting agricultural drought, which is a focus of DRI research. Yet, it is difficult to obtain soil moisture measurements from field surveys on large scales. Soil moisture often exhibits strong small-scale spatial and temporal heterogeneity, which further complicates the interpretation of observations. There are no consistent soil moisture monitoring networks to provide long datasets of large-scale soil moisture conditions in either Canada or the United States. Reconstructing the Prairie soil moisture history would therefore enhance our knowledge of drought characteristics and improve drought predictability.

Recent advances in the development and application of macroscale land surface hydrological models offer the potential to reconstruct and continually monitor and forecast spatial and temporal distributions of soil moisture over a large area. The Variable Infiltration Capacity model (VIC; Liang et al., 1994) is an example of such a land surface macroscale hydrology model. VIC uses a spatial probability distribution function to represent sub-grid variability in soil moisture storage capacity. Nijssen et al. (2001) used VIC to generate 14 years' worth (1980-1993) of global daily soil moisture at a resolution of 2° × 2°. Andreadis et al. (2005) reconstructed the drought history of the continental United States from 1920 to 2003 using VIC soil moisture and runoff at a resolution of 0.5° × 0.5°. Wu et al. (2007) recently applied VIC to generate 35 years' worth (1971-2005) of daily soil moisture over China at a resolution of 30 km × 30 km.

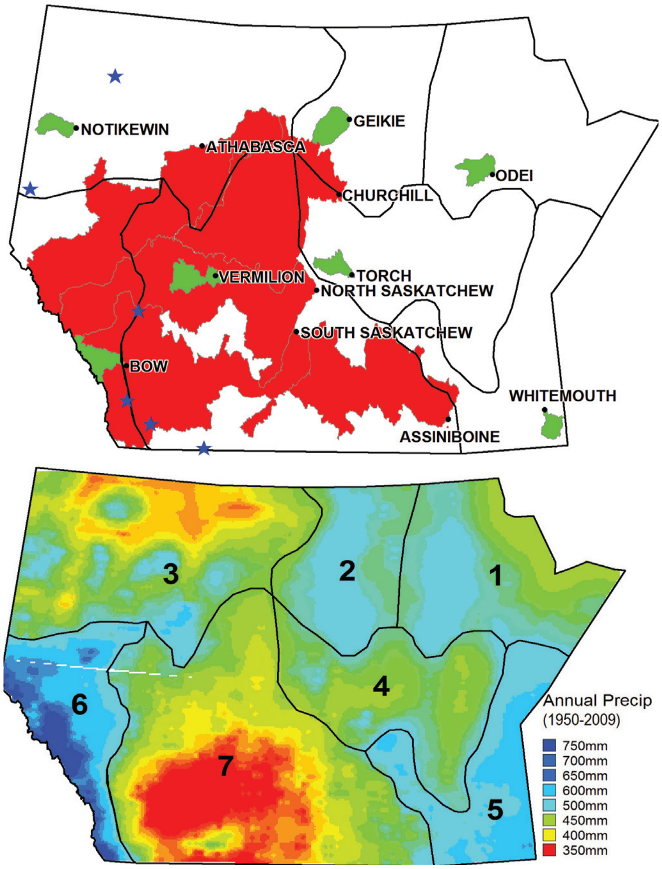

**Figure 1**. Upper panel: The seven calibration catchments and five additional validation catchments are coloured green and red, respectively; the stars show the six Alberta sites where *in situ* soil moisture measurements are available. Lower panel: The average annual precipitation from 1950 to 2005 over the Prairies, on which the seven VIC simulation regions (numerically ordered) are identified.

In this study, a real-time drought monitoring and seasonal prediction system has been developed for the Canadian Prairies (1,964,000 km$^2$). At present, the system uses VIC to simulate daily soil moisture values starting on January 1, 1950 and continually running through the present into the future with a lead time of up to 35 days. The VIC model is applied over a Prairie domain consisting of 4,393 grid points with a resolution of 0.25° × 0.25°. VIC is driven by daily maximum and minimum air temperature and precipitation from 1,167 meteorological stations for reconstructing and monitoring runs up to the present, by the operational Canadian Global Environmental Multiscale (GCM) model forecast, and by the operational 40-member super ensemble forecast of Canadian Meteorological Centre (CMC), and the operational CMC ensemble seasonal forecast for the forecast runs. A novel feature of our methodology is the use of both gauge and model data to drive VIC for real-time drought forecasting. The VIC model is well-calibrated and validated using observed hydrographs from 12 Prairie catchments (upper panel of Figure 1) with drainage areas ranging from 3,750 km$^2$ to 131,000 km$^2$ for the period January 1, 1975 to December 31, 2001. A novel feature of our VIC simulation is the consideration of non-contributing drainage areas in the calculation of model runoff. Seven VIC simulation regions (lower panel of Figure 1) are determined based on the average annual precipitation from 1950 to 2005 over the Prairies.

As a result, an estimation procedure to determine VIC parameters was developed and applied to catchments in which hydrographs are not available for the standard calibration process. Simulated soil moisture anomalies are in reasonably good agreement with *in situ* soil moisture measurements from six Alberta sites (upper panel of Figure 1). The calibrated VIC is then used to reconstruct, monitor, and forecast the Prairies' daily soil moisture values for three soil layers (0-20 cm, 20-100 cm, and 0-100 cm) for the period of January 1, 1950 to the present. VIC soil moisture is further used to calculate the Soil Moisture Anomaly Percentage Index (SMAPI) as an indicator for measuring the severity of agricultural drought. We simulate daily soil moisture and calculate SMAPI for the three soil layers at each of the 4,393 grid points over the Prairies. The results are publicly accessible online (http://www.meteo.mcgill.ca/~leiwen/vic/prairies/).

To illustrate the effect of non-contributing drainage areas on runoff calculations, we show in Figure 2 the observed and calibrated hydrographs at the outlets of the South Saskatchewan and Assiniboine catchments for both cases. The upper and lower panels of Figure 2 show a good agreement between the observed and VIC-simulated hydrograph with the consideration of the effect of non-contributing drainage areas in model runoff calculations, but the agreement is much less satisfactory without such consideration. For example, the Nash-Sutcliffe model coefficient ($E_c$) is significantly improved from -2.23 to 0.77 over the Assiniboine catchment when non-contributing areas are taken into account. About 61% of the Assiniboine Basin consists of non-contributing areas. In contrast, $E_c$ only increased negligibly from 0.8 to 0.81 at the Athabasca catchment; this catchment includes only 1.5% of non-contributing drainage areas.

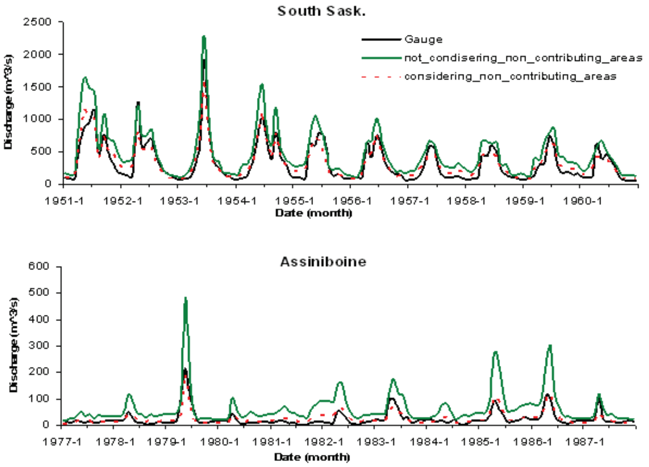

**Figure 2**. Upper panel: Comparison of observed and calibrated hydrographs at the outlet of the South Saskatchewan catchment, with and without the consideration of the effect of non-contributing drainage areas in model runoff calculations. Lower panel: The same as the upper panel, but for the Assiniboine catchment.

We show in Figure 3 the VIC reconstructed 56-year (1950-2005) average of soil moisture in the top 1 m for the Prairies, along with the 200 mm soil moisture, which outlines the very dry modelled areas. The 200-mm very dry threshold is adopted by Alberta Agriculture. Regional dry and wet areas can be seen clearly in the figure. An important finding shown in Figure 3 is the reconstruction of both the Palliser Triangle region and the Prairie Dry Belt (Jones, 1987) in the southern Prairies using the 200-mm very dry threshold. Based on the global 10-km soil profile dataset (Reynolds et al., 2000), sandy loam is identified as the dominant type of soil for both the Rocky Mountains in Alberta and the regions of north-east Saskatchewan and north-west Manitoba. The two sandy loam regions can be identified as very dry areas using the 200-mm threshold (Figure 3). Our finding is reasonable, as it is well known that moisture in soil columns cannot be easily retained in sandy loam soil due to large values of porosity and saturate hydraulic conductivity.

Recalling the lower panel of Figure 1 and the average annual precipitation from 1950 to 2005 and combining them with the panel showing the composition of soil textures over the Prairies, we suggest that low precipitation and loose soil contribute to the drought-prone characteristics observed over the Prairies.

SMAPI is expressed in the equation below, where Ø represents the current value of soil moisture and $SM_{av}$ is used here to represent its climatology:

$$\text{SMAPI} = \frac{\emptyset - SM_{av}}{SM_{av}} \times 100\%$$

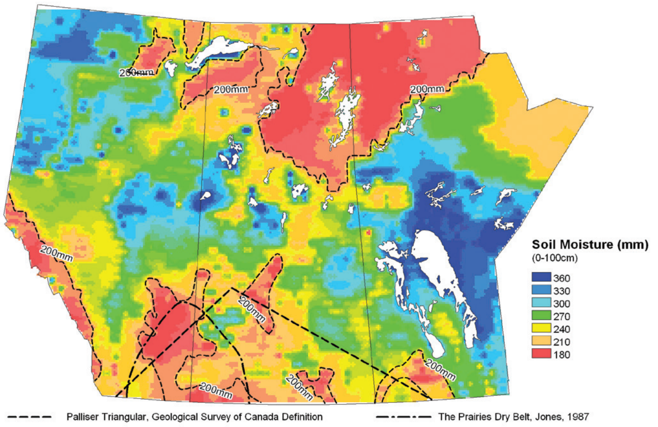

**Figure 3**. The VIC-reconstructed 56-year (1950-2005) average of soil moisture in the top 1 m for the Prairies. The 200 mm contour is shown; see text for discussion. The Palliser Triangle region and the Prairie Dry Belt in the southern Prairies are also shown.

We examined the dry and wet classification based on SMAPI over study domains in China prior to the current study. We calculated SMAPI values using observed soil moisture collected on the 1st, 11th, and 21st of every month from 1981 to 1999 at ten sites located in different regions of China. Figure 4 shows the frequency distributions of SMAPI for the ten sites as well as their average. It is clear that the latter pattern can be represented by a Gaussian distribution. SMAPI can thus be used to compare droughts in different regions. Based on analysis of drought data from the ten sites, SMAPI values can be classified in nine categories (shown in Table 1). Our proposed categories are similar to those of Palmer (1965).

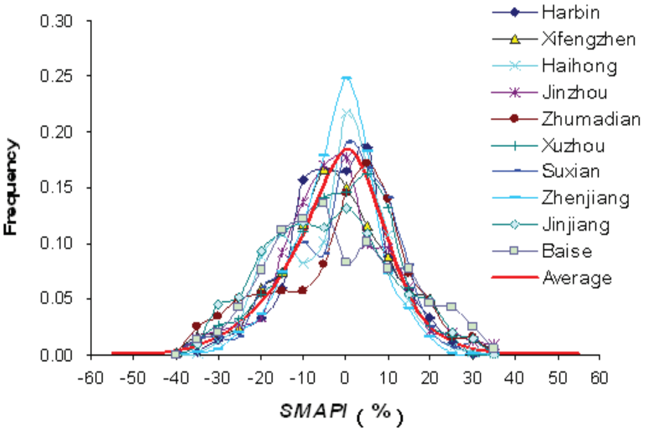

**Figure 4**. The frequency distributions of SMAPI (see text for discussion) for ten Chinese experimental sites together with their average.

The reconstructed VIC SMAPI can be used to explain historical drought events on the Prairies over the past 60 years. Figure 5 shows the SMAPI distributions of the three soil layers for April 20, 2002, together with the April 2002 SMAPI average in the top 1 m for the Prairies. The most recent Prairie drought of

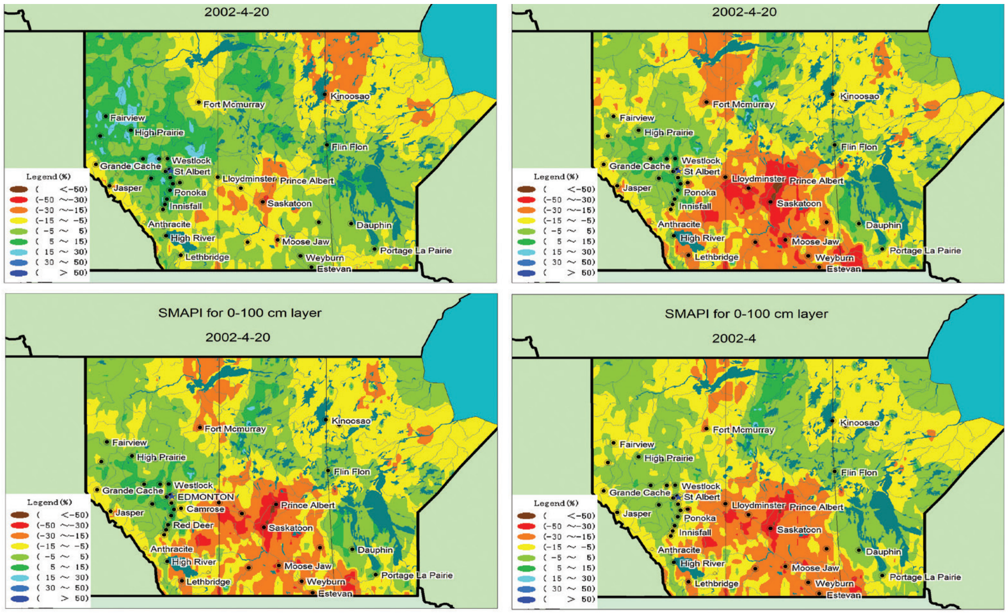

**Figure 5**. The VIC-based SMAPI distributions of three soil layers (0-20 cm, 20-100 cm, and 0-100 cm) for April 20, 2002, together with the April 2002 average of SMAPI in the top 1 m for the Prairies.

1999-2005 peaked during 2001 and 2002. Accordingly, the upper left panel of Figure 5 shows the distribution of SMAPI for the 0-20 cm depth. A few scattered moderate droughts (-30% < SMAPI < -15%; see Table 1) can be identified in the central and north-east regions of Saskatchewan and the north-west region of Manitoba, indicating a moderate situation of soil moisture stresses in the near-surface layer on April 20, 2002.

| Category | SMAPI | Average Frequency |
|---|---|---|
| Extreme drought | ≤ -50% | 0.005 |
| Severe drought | -50% to -30% | 0.020 |
| Moderate drought | -30% to -15% | 0.100 |
| Mild drought | -15% to -5% | 0.200 |
| Near normal | -5% to 5% | 0.350 |
| Slightly wet | 5% to 15% | 0.200 |
| Moderately wet | 15% to 30% | 0.100 |
| Very wet | 30% to 50% | 0.020 |
| Extremely wet | ≥ 50% | 0.005 |

**Table 1**. Soil moisture classifications based on SMAPI.

The situation is significantly different in the rooting zone of 20 cm to 100 cm, as shown in the upper right panel of Figure 5. Soil moisture memory in the deeper layer is much longer than that near the surface. Several severe droughts (-50% < SMAPI < -30%) and extreme droughts (SMAPI < -50%) can be clearly identified in the south-east areas of Alberta, the central to southern regions of Saskatchewan, and the south-west corner of Manitoba. An extreme drought had been occurring in the area between Saskatoon and Prince Albert on April 20, 2002, which is shown in the upper right panel of Figure 5. Not surprisingly, the distribution of SMAPI for the 0-100 cm depth (bottom left panel of Figure 5) is very similar to that of the rooting zone, as the calculation of SMAPI for the 0-100 cm depth takes 80% of the rooting zones' contribution. Daily SMAPI values can be aggregated into different temporal averages of specific periods (e.g., week, month, seasonal, annual) for diagnostic purposes, including drought onset, duration, cessation, areal extension, and severity. The April 2002 average of SMAPI in the top 1 m is shown in the bottom right panel of Figure 5. Large-scale droughts can be seen clearly in the south-east areas of Alberta, the central to southern regions of Saskatchewan, and the south-west corner of Manitoba. If we combine the April 2002 SMAPI average with corresponding daily SMAPI values, it is clear that these regions had been undergoing severe soil moisture stresses for the month of April 2002.

## Implications of the Results

We developed a real-time drought monitoring and seasonal prediction system for the Canadian Prairies. The system produces high-resolution (0.25° × 0.25°) daily soil moisture and SMAPI for three soil layers (0-20 cm, 20-100 cm, and 0-100 cm) starting on January 1, 1950 and continually running through the present into the future with a lead time of up to 35 days. The system is updated daily and the results are publicly accessible to interested stakeholders. Our study represents the first attempt in Canada to systematically reconstruct, monitor, and forecast daily soil moisture conditions for the Prairies using a macroscale hydrology model.

*Hydrologic Sciences*

# CANADIAN PRAIRIE DROUGHT HYDROLOGY

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*Dr. Alain Pietroniro is currently the National Director for the Water Survey of Canada. He has been with Environment Canada for the past 18 years and served as a research scientist and hydrologist for much of that time. He works out of the National Hydrology Research Centre in Saskatoon. Dr. Pietroniro's research focus has been on designing and implementing hydrological models and model components for applications development within the department. He has been involved with coupled atmospheric-hydrological modelling for climate change and land use change assessments on major drainage basins in Canada as well as coupled numerical weather prediction models for flood forecasting and extreme event analysis. Dr. Pietroniro has published over 50 refereed scientific journal articles, 80 conference or proceedings articles, and over 50 published abstracts. He has also edited or published chapters in numerous proceedings and textbooks on applications of geomatics in hydrology and surface water remote sensing. Dr. Pietroniro currently supervises graduate students at the University of Saskatchewan and sits on numerous graduate student advisory committees at the Universities of Saskatchewan and Waterloo.*

## Why the Research was Undertaken

Drought has important water resource implications on the Prairies: both snowfall and soil moisture are greatly reduced, which directly impacts streamflow and replenishment of water bodies. This profoundly impacts local water availability for farms, communities, and industry and greatly contributes to the social and economic devastation caused by the drought of 1999-2005. Drought studies in Canada have traditionally emphasized increased temperature and decreased precipitation. However, though it has been long recognized that water supply is also strongly affected by drought, the mechanisms by which surface hydrology is affected in the Canadian Prairie environment have been poorly understood. Because of several distinctive aspects of Prairie hydrology, traditional hydrological models fail in the region. There is a need to better understand the distinctive aspects of Prairie hydrology, especially during drought, and to incorporate this understanding into improved hydrological models for water resource prediction.

In more temperate regions, drought hydrology is most strongly influenced by summer rainfall. However, on the Canadian Prairies, despite the fact that snowfall comprises only one third of annual precipitation, over 80% of annual runoff is derived from snowmelt. Snowmelt runoff efficiency is high because snow is redistributed by wind to drifts in wetlands and stream channels. Frozen soils restrict infiltration of snowmelt water and cold soils so that a larger percentage contributes to runoff and inactive vegetation results in minimal evaporation losses during snowmelt periods. The accumulation and melt of snow are therefore of primary importance in controlling Prairie runoff generation. However, the effect of drought on winter snowpacks and therefore runoff generation is relatively unknown.

Evapotranspiration, precipitation, and runoff govern the surface water balance, and of these evapotranspiration is the least understood and measured. Evapotranspiration rates are influenced by meteorology but are also strongly associated with soil moisture, plant growth, and streamflow during droughts. This association is complex, as evapotranspiration is both affected by and has an effect on these factors. Better methods to estimate evapotranspiration are needed to understand how the water balance is affected by drought. Employing these methods to estimate evapotranspiration could contribute to better descriptions of the dynamics of drought hydrology.

The Prairie landscape is characterized by numerous small post-glacial depressions known locally as "sloughs" or "potholes" that are important wetlands for wildlife and groundwater recharge. During dry conditions, the majority of these wetlands do not discharge to any natural external drainage system, forming closed drainage basins. Depressional wetlands occasionally connect to one another during wet conditions through the "fill and spill" mechanism. A better understanding of how these wetlands dry out and disconnect during drought and reconnect as drought ends is needed.

## The Research that was Undertaken

Research was undertaken on snow hydrology, evapotranspiration, and drainage basin modelling, key areas needed to better describe, understand, and predict Canadian drought hydrology. These are areas of hydrology in which the Canadian Prairies are very distinctive and for which there are no analogues elsewhere in the world. The research therefore had both fundamental and applied elements.

The research was informed by detailed field studies at the St. Denis National Wildlife Area, the Duck Lake aquifer, and the Brightwater Creek basin, all within 100 km of Saskatoon, and the Smith Creek Research Basin near Langenburg, Saskatchewan (near the Manitoba border). The field studies included direct measurement of evapotranspiration using specialized wind and humidity sensors, measurement of changes in snowpack, soil moisture, groundwater, streamflow, and wetland levels, and observations of horizontal water transport by blowing snow and runoff from wetlands in spring. St. Denis is a classic upland complex of poorly connected, internally drained wetlands with no true drainage basin or stream. Duck Lake is a confined aquifer for which evapotranspiration could be linked to groundwater levels. Brightwater Creek is a well drained, level agricultural area that drains to a stream, and Smith Creek is a poorly drained agricultural basin with a high wetland density but some drainage to a stream. Since these field studies were all begun after the 1999-2005 drought had ended, archives of field studies at St. Denis, Bad Lake Research Basin in south-western Saskatchewan, and the Lethbridge Ameriflux station were also used to show the hydrology in extremely dry conditions. These field data not only better informed the descriptions of Prairie hydrology that were important for understanding drought, but also provided testbeds for evaluation of new hydrological models that would be developed to better predict drought impacts on water resources.

The understanding gleaned from field studies was used to improve the Cold Regions Hydrological Model (CRHM) and the Modélisation Environnementale Communautaire (MEC) Surface and Hydrology Model (MESH) so that the Prairie drought could be better described and future droughts better predicted. The models operated at two scales and for two different purposes. At the small scale, the CRHM was modified to better characterize Prairie blowing snow, evapotranspiration, soil moisture dynamics, and the fill and spill of wetlands. This system was applied to Bad Lake, St. Denis, the Smith Creek drainage basins, and then across the Prairies in small representative drainage basins that characterize the surface hydrology of small streams in well-drained and wetland landscapes. The CRHM was also used to develop new indicators of drought hydrology, which show the probability of soil moisture levels, snowpacks, or streamflow being exceeded based on a 46-year model run. Since these indicators do not always coincide for drought, they each provide valuable information for describing the progression and cessation of various aspects of hydrological drought over space and time. At the large basin scale, MESH was tested at Duck Lake and Brightwater Creek and then applied to the South Saskatchewan River basin. This model is part of Environment Canada's environmental prediction framework and is used to improve weather model forecasts as well as operational assessments of water supply. It also forms the basis for land surface modelling in regional climate models. The CRHM and MESH represent the most advanced application to date of hydrological models to the Prairies and have provided a wealth of information on drought hydrology for snowpacks, streams, aquifers, soil moisture, and wetlands, which were not monitored during the recent drought and were therefore relatively unknown. The project has also contributed to DRI outreach by sponsoring modelling courses in Winnipeg, Calgary, Edmonton, and Red Deer that have trained users in government, university, non-profit groups, and industry in how to apply these freely available models.

## Summary of Findings and their Importance

Examination of the snow hydrology of the 1999-2005 drought provided the first descriptions of how drought affects fall, winter, and spring hydrology on the Prairies. The drought was associated with colder, drier winters and these caused reduced blowing snow redistribution as vegetation was able to hold the relatively light snowfalls in place. The reduced snowpack tended to infiltrate into frozen soils rather than form runoff. So while spring soil moisture recovered from a dry fall in many areas, runoff dropped to extremely low values, causing many small streams not to flow at all in the spring of 2001. Spring wetland recharge was also minimal in drought years due to the lack of blowing snow to form drifts in wetlands and lack of runoff from spring snowmelt in the fields surrounding wetlands. The early snowmelt replenished soil moisture but did so in March instead of during the normal April melt, leaving a longer summer for soils to dry out from evapotranspiration.

Evapotranspiration can be restricted during drought, as it is governed by the soil moisture supply that is available to plant roots. However, the warmer summer weather that is characteristic of droughts promotes higher evapotranspiration where locally adequate soil moisture supplies permit. During drought, plants attempt to access deep soil moisture, but in areas where it is depleted, evapotranspiration is reduced. Where soil moisture supplies remain adequate during drought, higher-than-normal evapotranspiration rates occur. As a result, the recent drought produced both the highest and lowest evapotranspiration rates that can be sustained on the Prairies. The implications of increased spatial variability of evapotranspiration during drought have not been fully assessed in terms of weather forecasting.

Wetlands were severely depleted by reduced snowdrifts and snowmelt runoff throughout the Prairies. As they control the contributing area for runoff to streams and larger lakes, depleted wetlands caused much of the Prairie drainage system to disconnect during the spring melt and throughout the summer in the worst years of the drought. Connectivity depends on the spatial distribution of surface storage in wetlands (Figure 1). Many small- to moderate-sized streams recorded no streamflow whatsoever for at least one year of the drought, while others were intermittent, depending on connectivity. However, the wetlands also mitigated the drought, and where large numbers were intact, the impact of the drought on streamflow was delayed and reduced compared to areas with drained wetlands or good drainage. This hydrological memory effect has now been incorporated in various models of the drought.

Hydrological models can now simulate the hydrology of small streams, wetlands, and the South Saskatchewan River basin during drought. These models show that the hydrological drought in the 1999-2005 period migrated across the Prairies; it intensified initially in the western Prairies but then moved north and east while subsiding in the south (Figure 2). This migration substantially alleviated the hydrological drought in individual river basins and so while meteorological drought was extensive for much of the 1999-2005 period, hydrological drought in individual river basins was severe for less than three years. Extensive wetlands have the effect of reducing hydrologic drought except where they were artificially drained because they

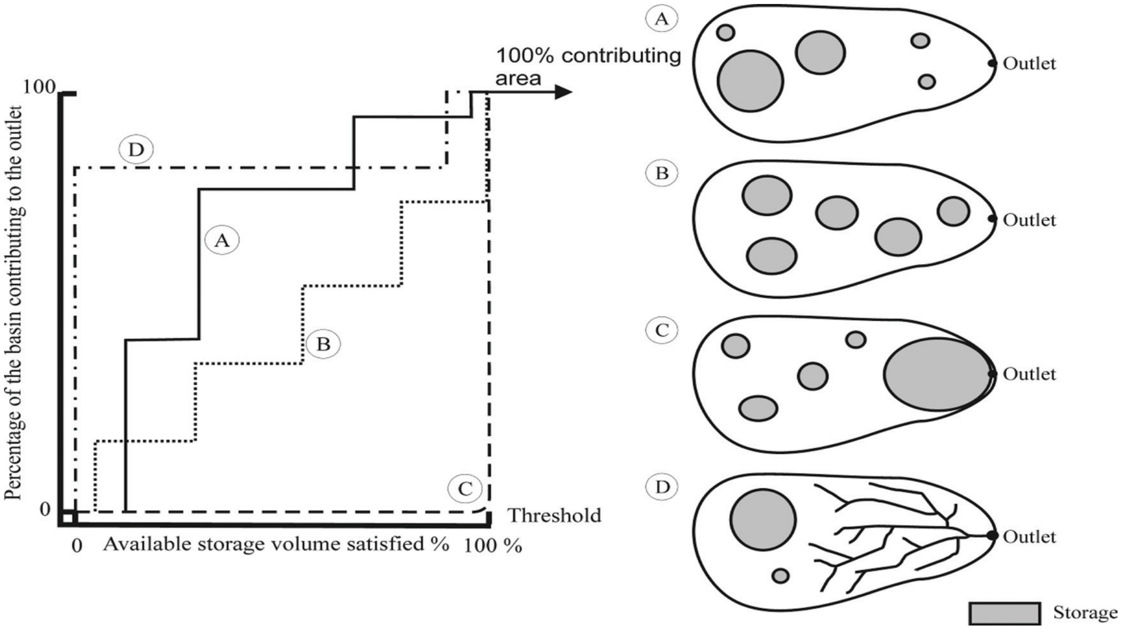

**Figure 1**. Conceptual curves expressing the relationship between basin storage and contributing area in a Prairie wetland landscape.

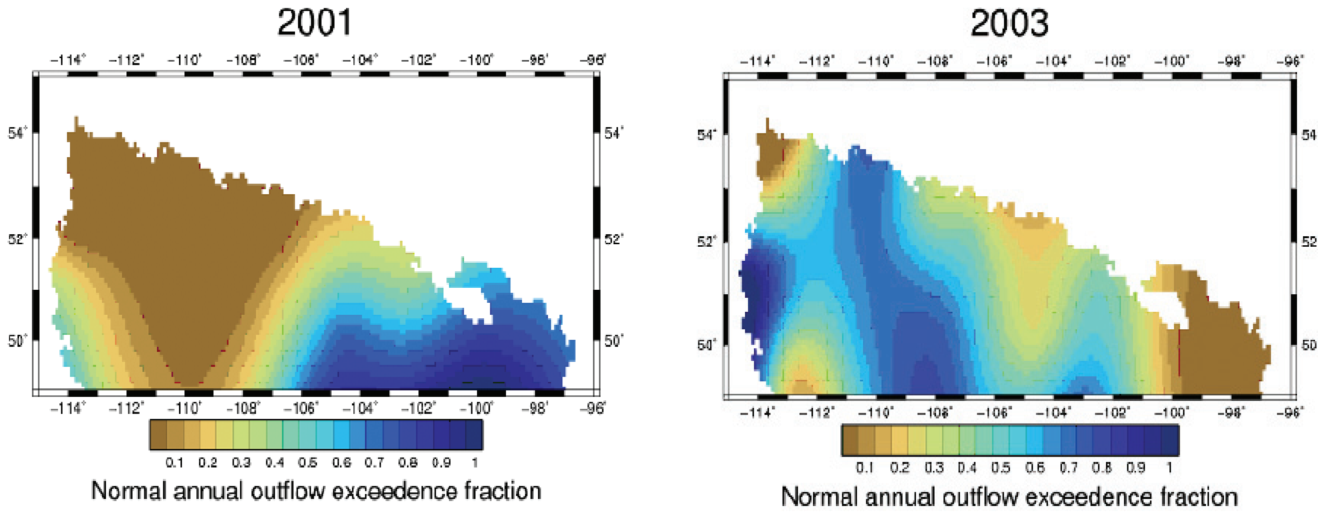

**Figure 2**. Map of the Prairie agricultural region showing hydrological drought intensity as the exceedence fraction for the annual outflow of a small stream discharging from a well-drained basin in a) 2001, when the drought focussed on Alberta and western Saskatchewan, and b) 2003, when it was most severe in Manitoba and parts of the northern Prairies.

retain a "memory" of antecedent wet conditions. However, there was no evidence of wetland-induced memory in the cessation of drought. In 2005 the hydrological drought ended as quickly for wetland-dominated basins as for well-drained basins because of the extraordinarily wet summer and fall. Indicators for snowpack, soil moisture, and small stream outflow were in the driest 10% of conditions in the last 50 years during the drought and wetter than 90% of the years by 2005. Due to low snowpacks, the South Saskatchewan River experienced extremely low flows during the recent drought and the glacier contribution to these flows was smaller than expected due to the recent decline in glacier area – they no longer extend over enough of the Rocky Mountains to make significant contributions to major river flows during drought, and now contribute less than 3% of the flow of the South Saskatchewan River.

## Implications of the Results

Because of the importance of snowmelt runoff to streamflow generation on the Prairies, hydrological drought is not reliably connected to the occurrence of summer precipitation deficits in the agricultural region. As a result, summer agricultural droughts may not be congruous with the spring streamflow and winter snow deficits that drive hydrological drought. This is important to land managers who might make use of available water supplies when normal dryland farming practices are ineffective due to summer drought. For instance, wetland conservation can work to alleviate the hydrological impacts of drought and sustain streamflow through short drought periods. With a few exceptions, hydrological droughts in major rivers are more affected by Rocky Mountain snowpack than by Prairie meteorology. For conditions when mountain snowpacks remain high but Prairie soil moisture is low, irrigation options should be investigated. Unfortunately, in the recent drought both mountain snowpack and Prairie soil moisture were low, which severely limited management options. Fortunately, the hydrological drought migrated during the 1999-2005 drought, which alleviated the duration of drought in individual river basins. In the future, coupled hydrological and atmospheric models should be able to better predict drought evolution and water resource impacts, but there is great concern that water management will become more difficult due to increasing water demand across the Prairies.

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# THE RESPONSE OF GROUNDWATER LEVELS, WETLANDS, AND LAKES IN WESTERN CANADA TO DROUGHT

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## Background and Introduction

The 1999-2005 drought had a marked effect on groundwater levels and Prairie wetlands. There was a multi-year decline of the water table over the entire region and many wetlands dried out altogether, even those containing ponds that rarely fall dry. These effects of drought in turn reduced water availability from shallow wells and from dugouts and streams, which resulted in increased stresses for wildlife, particularly waterfowl, and further impacted agriculture.

The effects of drought on groundwater levels can be best characterized by the decline of the water table, which was recorded in shallow observation wells in surficial sand and gravel aquifers. Approximately 20 to 30 such wells are operated by provincial groundwater agencies. The hydraulics of groundwater flow in these shallow aquifers function such that the effects of pumping from water supply wells are not likely to be felt more than a few hundred metres away from the supply wells. Very few of the shallow observation wells are therefore affected by pumping. These shallow wells are situated in areas of sandy soils, which also means that the land use is non-intensive and not subject to much change. For most of these wells, the surrounding land is in permanent pasture or unused land. The shallow wells thus provide a useful record of the effects of drought on the water table with little or no impact being felt from pumping or land use changes. Many observation well records are also available for deeper aquifers, but these records are much more subject to the effects of pumping from supply wells that may be tens of kilometres away.

For much of the Prairies, the shallow geology does not consist of sand and gravel, but of clay or clay-rich glacial tills, which have low permeability and are not suitable for water supply wells. Most of the cropped land area lies in these geological settings, which are characterized by loamy soils. There appear to be no useful long-term observation well records for such settings and there is little information on how the water table fluctuates during droughts.

Observation well records for Alberta, Saskatchewan, and Manitoba were gathered from the provincial records and compiled in a common format to establish a Prairie-wide database. The water level records come in various formats, with time steps varying from hours to months. Since most of the Saskatchewan records are in the format of monthly median water levels (i.e., the mid-point between the highest and lowest recorded water level for the month), the records from the other provinces were reduced to the same monthly median format. This approach produces a compact database of groundwater levels that smooths out day-to-day variations but shows the longer-term variations.

The records for shallow wells in Alberta and Saskatchewan are shown in Figures 1 and 2. The records for Manitoba are still being checked for interference effects. A few well records were eliminated from the compilation because they are clearly affected by pumping or by other known interference effects, such as sewage effluent irrigation or an adjacent lake or wetland.

The water table changes recorded by the shallow observation wells clearly show a general decline between about 2000 and 2003 in response to the drought. The average decline was about 0.5 m, which corresponds to a change of water storage at the water table of about 150 mm of water, assuming a specific yield of the sand and gravel of about 0.30. After 2003 the water table levels in most of the wells levelled out. Nearly all the wells show the typical annual pattern: a sharp rise of water levels after spring snowmelt and a gradual decline during the rest of the year. The latter results from evapotranspiration losses to the ground surface and vegetation as well as from seepage to nearby surface water bodies, such as springs.

In most of Saskatchewan the water table recovered in 2005, one year after the meteorological drought ended. Presumably, the heavier rains of the summer of 2004 mostly satisfied the accumulated moisture deficiency in the overlying soils and infiltrated water did not penetrate to the water table until the snowmelt period in the spring of 2005. In Alberta it appears that the water table was slow to recover from the effects of the drought.

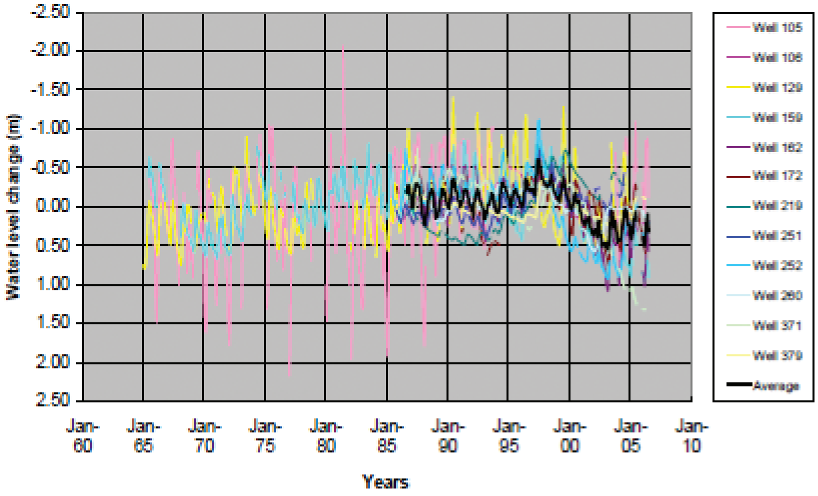


**Figure 1**. Observation well records for shallow water table wells in Alberta. Monthly median values were calculated on the basis of data provided by Alberta Environment.

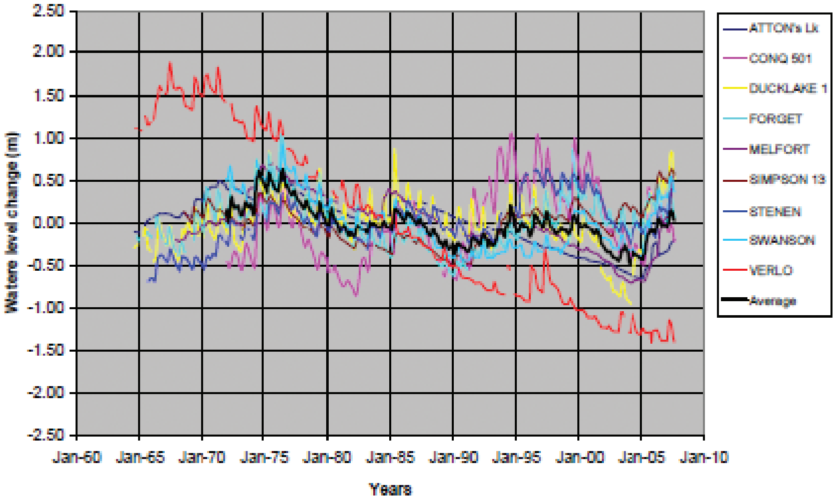


**Figure 2**. Observation well records for shallow water table wells in Saskatchewan. Data were provided by the Saskatchewan Watershed Authority.

Some wells show anomalous behaviour. This is particularly the case for the Verlo well in Saskatchewan, which is located within the Great Sand Hills area of south-west Saskatchewan. The water level in this well has declined almost continuously since 1971, but the cause of this decline has not been identified. The records shown in Figures 1 and 2 indicate that, other than the Verlo well, there has been no general decline of the water table over the last four or five decades, although the lack of recovery in Alberta after the recent drought merits further attention.

During DRI, a dense network of observation wells was set up in the West Nose Creek watershed near Calgary to monitor the recovery of water level in deep bedrock aquifers (Grieef and Hayashi, 2007). This is a pilot study to examine the usefulness of community-based monitoring programmes, where the data are recorded for private water supply wells. Such an approach is expected to provide the critical data to distinguish between the effects of natural processes (e.g., drought) at the groundwater level and anthropogenic effects such as heavy pumping. Figure 3 shows the water level measured in four monitoring wells located in different parts of the watershed. These wells are all screened in the Paskapoo Formation aquifer system (Grasby et al., 2008) with the screen depth ranging from 25 m to 65 m. All wells show recovering trends after the drought and responses to annual recharge events, although the magnitude of responses varies among the wells.

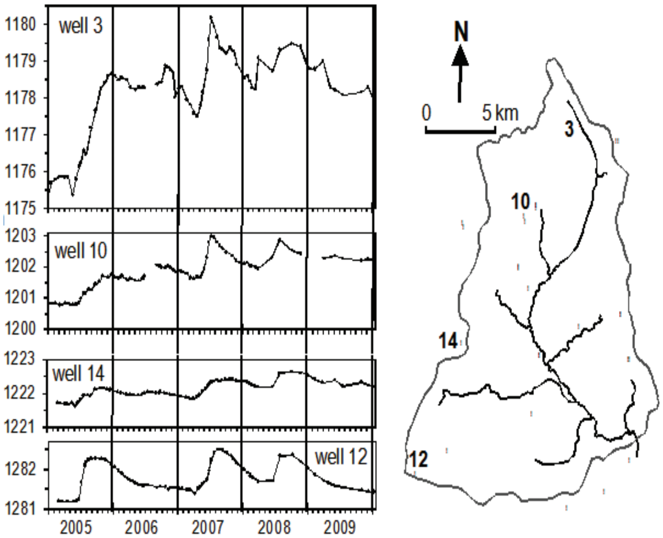


**Figure 3**. Map of the West Nose Creek watershed showing the location of groundwater monitoring wells and water level (metres above mean sea level) measured in wells 3, 10, 12, and 14. Dotted lines in the graph indicate the beginning of each year and tick marks indicate the beginning of each month.

The water levels in Prairie wetlands are closely connected with the shallow water table in their vicinity. Most of the smaller wetlands located in the higher portions of the landscape function as sources of groundwater recharge, although the principal source of recharge is probably represented by the small temporary puddles that occur everywhere during snowmelt or after heavy rains. The annual pond counts that are conducted each spring, in association with the waterfowl census, provide a useful overview of the state of wetlands on the Canadian Prairies. Figure 4 shows how the total number of ponds has varied over the years. This plot shows that the number of ponds declined to a minimum in 2002 and recovered to near-average conditions in 2005. A comparison with the water table records in Figures 1 and 2 shows a strong correlation between the longer-term cycles of pond numbers and groundwater levels. This observation is not surprising, considering that both groundwater recharge and wetland replenishment depend on the availability of spring snowmelt water for infiltration and runoff.

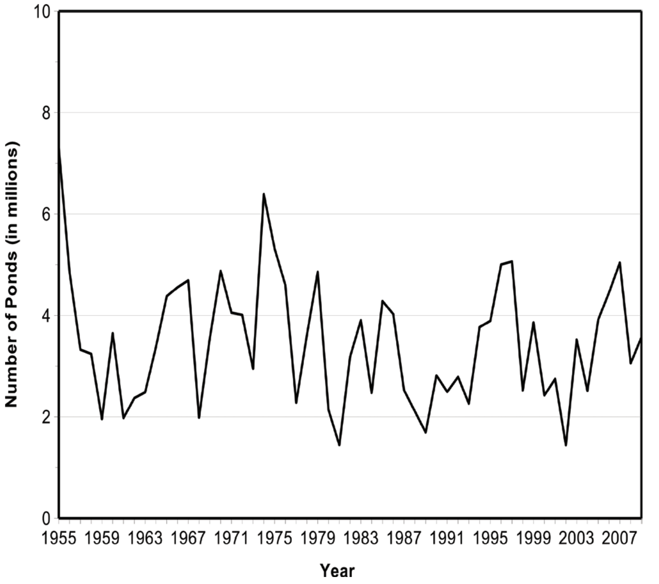


**Figure 4**. Total estimated number of ponds for the Canadian portion of the Prairie pothole region. Data provided by the Canadian Wildlife Service.

The drought also affected the water levels in Prairie lakes, causing a decline of 0.5 m to 1 m. For some lakes that normally have an outflow, this decline was sufficient to drop the water level below the level of the sill so that outflow from the lakes ceased altogether. For lakes that were already not connected to outflow, the drought further exacerbated the ongoing decline of water levels, as shown in Figure 5.

## Conclusion

The effects of the drought were clearly marked by the decline of groundwater levels, the drying out of wetlands, and the lowering of water levels of lakes in the Prairie region. The effect of the drought on groundwater levels appears to have lingered in parts of Alberta. The water levels for many closed-basin Prairie lakes

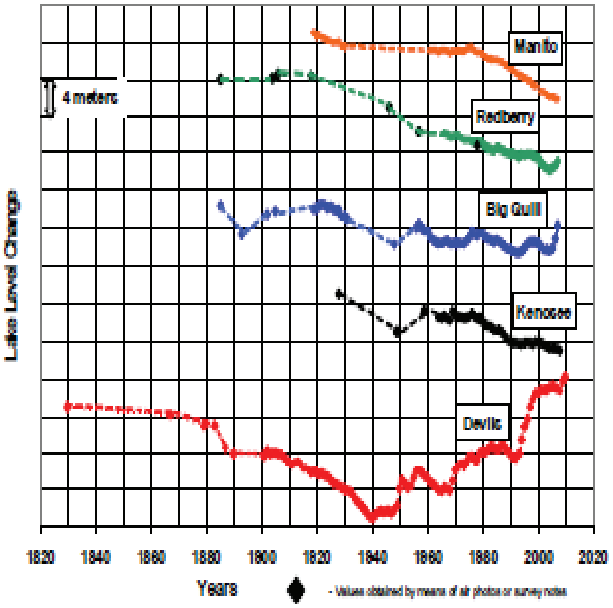


**Figure 5**. Long-term water level changes in closed-basin lakes (adapted from van der Kamp et al., 2008). For locations of the lakes, see Figure 6.

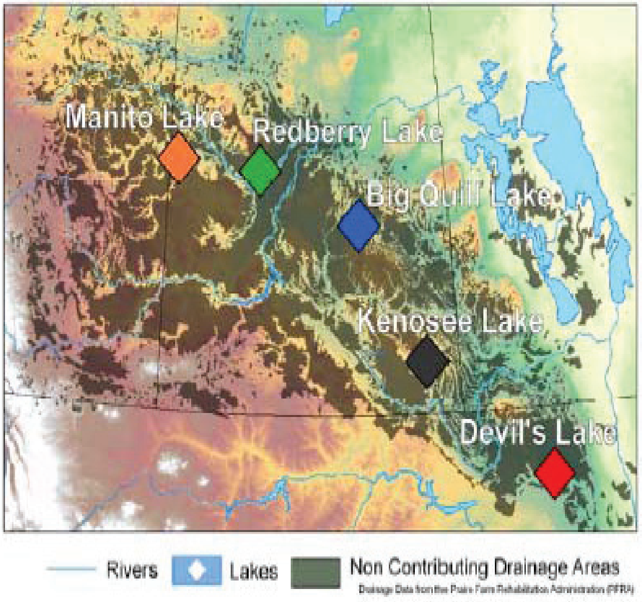


**Figure 6.** Locations of the lakes referred to in Figure 5.

were already in a declining phase for much of the twentieth century.

The numerous small Prairie wetlands, also called "sloughs" or "potholes," are very sensitive to drought, owing to the shallow depths of the ponds in these wetlands. Virtually all wetlands dried out in the parts of the region in which the drought was most severe and long-lasting. Large deep lakes are sensitive to longer-term variations of wet and dry conditions and the water levels in such lakes are subject to large variations over time scales of decades and even centuries. Groundwater levels were affected, but even after several years of drought the groundwater levels did not decline a great deal. Groundwater can be viewed as a secure source of water during droughts because it represents a large reservoir of water that is not greatly affected by year-to-year variations in recharge and is largely protected from evaporation by its depth below the ground surface.

*Hydrologic Sciences*

# DROUGHT PREDICTION AND VULNERABILITY OF AQUIFERS UNDER CLIMATE CHANGE

*Allan Woodbury, Ken Snelgrove, Lei Wen, Charles Lin, Alireza Hejazi, and Youssef Loukili*

*Dr. Allan Woodbury, P.Eng., is a Senior Professor in the Department of Civil Engineering, Water Resources/Geotechnical Divisions at the University of Manitoba. Since 1987, Dr. Woodbury has taught undergraduate and graduate water resources engineering and groundwater hydrogeology at McGill University and the University of Manitoba. He has established a productive research programme in hydrogeology. Dr. Woodbury has an extensive publication record in pioneering probabilistic methods, incorporating temperature measurements in hydrologic analysis, aquifer characterization, and the solution of ill-posed problems. He has received numerous invitations to speak at conferences and workshops, including the American Geophysical Union, the National Groundwater Association, and the Geological Society of America, as well as other universities and private organizations. Dr. Woodbury has served as an advisor to various governments, utilities, engineering companies, and organizations, including Atomic Energy of Canada Limited. He is currently a specialist consultant to the Saskatchewan government on potash and uranium tailings contamination. He also formerly collaborated with the Center for Nuclear Waste Regulatory Analysis in San Antonio, Texas for work at the Yucca Mountain nuclear repository. Dr. Woodbury's own professional efforts centre on the role of groundwater in geotechnical, mining, environmental, and water supply issues, particularly in a regulatory framework. These efforts involve investigations, assessment of remediation methods for contaminated waters and soils, water supply quality and quantity, engineering design, and the development and application of regulatory guidelines.*

## Background and Motivation

How will climate changes such as a recurring drought impact Manitoba's groundwater resources? The answer is not clear. It has been widely accepted, however, that climate change will have an impact on the atmosphere and hence our water resources. To assess the effects of atmospheric changes on groundwater resources (and how we might adapt to them), a multi-disciplinary study based on a large sand and gravel aquifer system, known as the Assiniboine Delta Aquifer (ADA), is being conducted in Manitoba.

The need for research that targets the effects of climate change on groundwater and agriculture is documented by climate change studies (Canada, 2002; Rivera et al., 2003). Although considerable research has been conducted on Prairie drought, there are numerous gaps in our knowledge. These include, for example, dynamics of the atmosphere, thresholds for precipitation events, non-linear linkages between the atmosphere and surface soil, and groundwater storage variations. While our work does not address issues of drought directly (past and current climates), it does attempt to address the atmosphere, surface soil, and subsurface as an integrated system, and it is from this point of view that advances in this branch of environmental research will likely occur. Possible interactions between engineering and economics will lead to cost-effective solutions, which may in turn be more easily implemented as climate changes become more acute.

The ADA has been selected for this study because of its importance to the Manitoba economy and the availability of the extensive data that is required to characterize the region. The ADA centres on the community of Carberry, Manitoba, which has a growing potato industry. This relatively new industry owes its existence to the sandy loam soils of the region, which are essential for potato growth, and to the availability of abundant groundwater resources, which are needed for irrigation and food processing. Of the groundwater resource consumers, the potato industry is the largest and uses approximately half of the current aquifer allocation limit. Value attached to the potato crop was estimated at $60 million in 1996, the majority of which supports the export market. Projections indicate that Manitoba may soon surpass Prince Edward Island as Canada's leader in potato crop production (Winnipeg Free Press, 2003). Previous economic studies by Kulshreshtha (1994) estimated aquifer water value at between $85 million and $460 million using an economic efficiency approach, and between $795 million to $4 billion using a regional development perspective. While there is some debate regarding the assumptions in this calculation, it is clear that a significant part of the aquifer's social value includes the increase in economic activity directly related to the aquifer water supply. As a result, much attention has been paid to supporting this resource and the value-added industries it has spawned.

## Technical Objectives

Our long-term goal is to develop an efficient hydrological and numerical coupling of atmospheric processes. This has been achieved by coupling the Canadian Land Surface Scheme (CLASS) with groundwater flow (rewrite of CLASS2.6/groundwater) and with the atmosphere through accurate boundary conditions. We successfully benchmarked our improved version of the CLASS, which we refer to as Soil Atmosphere Boundary, Accurate Evaluations of Heat and Water (SABAE-HW). Intercomparisons to Simultaneous Heat and Water (SHAW), CLASS, HYDRUS-1D, and HELP3 ensure the applicability and viability of our code. The coupling strategy was chosen for efficiency and convergence reasons, among others. Efforts have focused on verification of SABAE at the Boreal Ecosystem Atmosphere Study (BOREAS) field site in Saskatchewan (Figure 1). We plan to simulate a broad part of the Canadian Prairie Provinces using both CLASS and SABAE as the underlying land surface schemes. We also plan to begin numerical programming, with the goal of ultimately coupling SABAE with the Canadian Global Climate Models (GCMs) in order to allow for more accurate exchanges of water and energy fluxes between the atmosphere and the earth surface. In doing so, we believe that we are taking the right steps toward our main goal: developing and using the adequate "toolbox" of numerical simulators for drought studies over the Prairies. The overall objective remains to assist DRI's research efforts to understand, assess, and quantify the evolution of drought. The inclusion of human practices in each of the model components (agriculture, pumping, wastes, and so on) will allow us to study their influences on climate variability and change.

Our generalized approach consists of using physically-based mathematical models of both the land surface and groundwater systems to predict changes in water quantity given drivers of future atmospheric climate and adaptive behaviours dictated by value-based economic analysis.

## Description of Research Undertaken

Our developed version of CLASS (SABAE-HW) has two new main features: the soil column depth and layers can be chosen according to any desired application, and the water table boundary condition can be used. The code input and output files are designed so as to be clear and practical for any user.

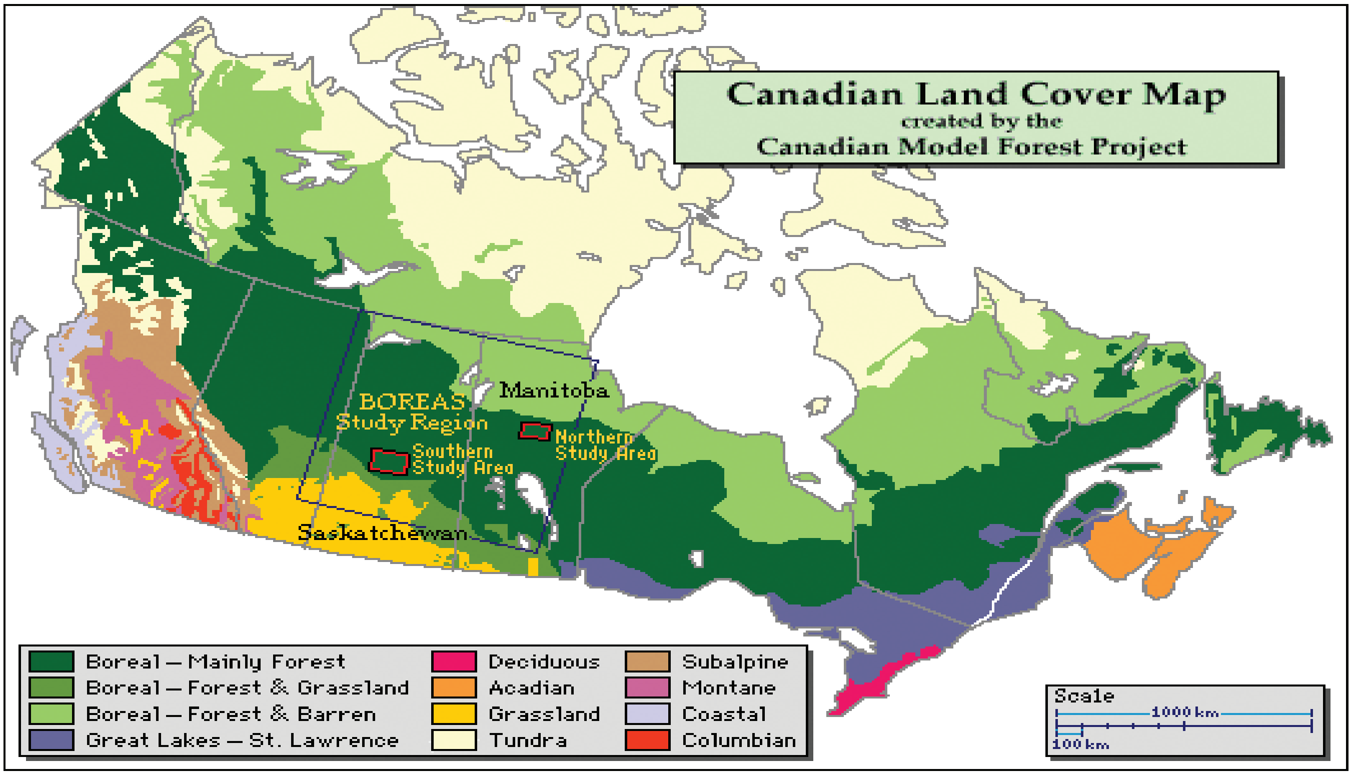


**Figure 1**. BOREAS field site.

We progressed in benchmarking SABAE-HW using actual atmospheric and soil data related to Pine Creek North, one of the thirteen sub-basins of the ADA. Using up to five years' worth of standalone runs of SABAE-HW, SHAW, and CLASS sheds light on the quality of results and verifies the applicability of our code in field situations. Indeed, contrasting solutions computed by the three codes (for variables including evaporation, water pond, snow depth, moisture, and temperature, for example) shows that SABAE-HW provides more accurate predictions than the original version of CLASS(2.6) that we reviewed.

Another important advance concerns the development of SABAE-HW3D (gCLASS), which actually couples the SABAE-HW one-dimensional soil columns with a two-dimensional horizontal groundwater flow model. The generic domain under study is subdivided into soil columns whose surface areas represent GCM grid squares. The depths of columns extend into the saturated zone, where a water table lower boundary condition is prescribed. In each column the unsaturated flow is forced by the corresponding meteorological data, and the moisture (liquid and frozen) and temperature profiles are computed by SABAE-HW using a half-hour time step. The horizontal flow in the saturated zone is described by a vertically integrated model incorporating a storage term and discretized using a finite volume scheme operating on the same GCM quadrilateral mesh. Since the saturated flow model affords larger time steps, bottom drainage from the soil columns are summed up and input as cell recharge. Meanwhile, as the water table fluctuates, an individual column's mesh is allowed to deform. This physically-based coupling strategy was selected for its superior ability to provide stable and consistent results. In fact, the convergence to steady-state situations in both the unsaturated and saturated zones is demonstrated by many validation numerical tests. Moreover, the code was successfully benchmarked against the finite element code Seep/W (Geo-Slope International, 2002) for steady and transient groundwater flows through different soil types.

Verification of the model has been attempted at the southern Old Jack Pine site at the BOREAS Saskatchewan field station (Figures 1 and 2). This is a very rich area in terms of hydrological and meteorological data and it was chosen to prove the accurate performance of SABAE. The area's soil type generally consists of sand or sandy loam. Atmospheric data, including long- and short-wave radiations, precipitation, air temperature, wind speed, and specific humidity were available in 30-minute periods in 2005. Since SABAE has been developed for time steps of 30 minutes, we had a great source of data to run this code. The site's vegetation type consists mostly of very sparse green alder and was therefore classified as a need leaf in SABAE. Parameters related to this class (maximum and minimum leaf area indices, maximum heights, visible albedos, canopy mass, near-infrared albedos, and vegetation rooting depth) were collected. Based

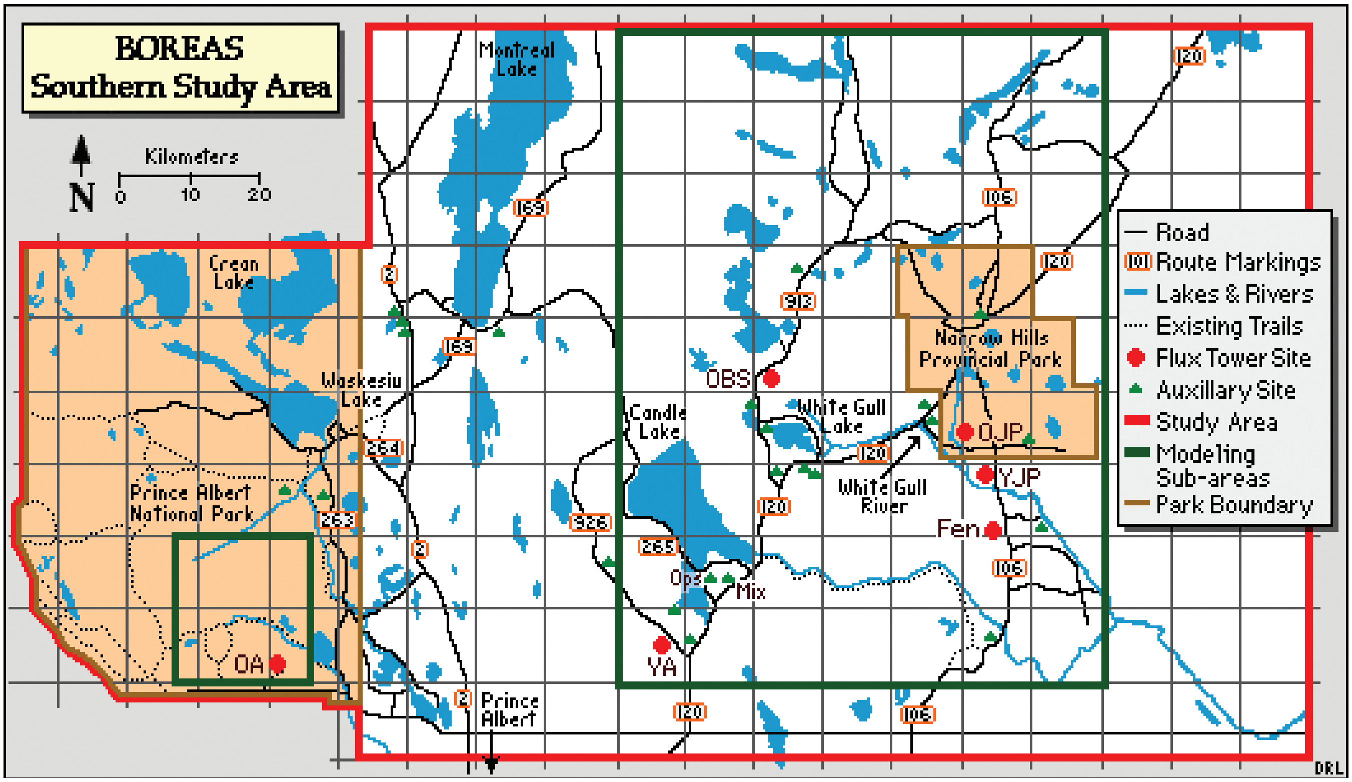


**Figure 2.** Old Jack Pine field site, courtesy of Garth van der Kamp.

on the available data on the BOREAS website, six layers were applied for a soil column. The two first layers are 15 cm thick, while the rest of layers have a thickness of 30 cm. The total depth of soil column is 150 cm. We have two options for imposing the boundary condition at the bottom of the grid: water table and unit gradient (UG). The UG boundary condition refers to free drainage from the soil column into underneath layers and was considered a lower boundary condition. Furthermore, we used the fixed point, based on the observed data (soil moisture and soil temperature), for the upper boundary condition. In addition, the exact value of observed data at t=0 was applied for initial conditions.

Since SABAE measures the value of soil moisture at the middle of each layer, we compared the results of SABAE with observed data at depths of 7.5 cm, 22.5 cm, 45 cm, 75 cm, and 115 cm. Unfortunately, the exact values of observed data at these points were not available. Instead, we used the average of two layers for observed data and then compared them to the results of SABAE. The comparison between the results of SABAE and the observation field data shows that there is reasonable accuracy between the results of the code and the measured data with respect to the volume water content.

## Summary of Findings

Successfully linking all the physics of water cycle processes first depends on properly coupling the atmosphere, land surface, and groundwater components. The value of our efforts to achieve this goal through developed numerical methods was demonstrated over the course of our progress. The multi-layer version of SABAE, with its user-friendly input/output, allowed us to persuade other researchers to lead comparisons of their field measurements and publish joint papers. The time we devoted to understanding and using other models (SHAW, HYDRUS-1D, and HELP) gave us more confidence in our coordination and procedures. We then expanded our partners in a cross-disciplinary framework with Engineering and Applied Sciences (Memorial University of Newfoundland), Geology (University of Calgary), and Biosystems Engineering (University of Manitoba). Only a few researchers are on this critical path, which once again proves that we are participating in the advancement of this modern hydrological coupling trend by using more powerful numerical and optimization tools.

It should be noted, moreover, that SABAE-HW keeps most of the improved CLASS surface physics, which gives it the potential to attract more attention and partnership. We encourage the use of SABAE-HW by Canadian students, trainees, and engineers researching the effects of climate on soil moisture, temperature, freezing, and thawing. We are also considering a special package for concerned public partners, which would enhance the outreach of the computational prediction concept (local and regional) and in turn help fine-tune weather conditions by communicating the results of simple data collection activities.

## Implications of Findings

In addition to support from the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) for our work on drought, we received additional funding from the Canadian Water Network (CWN).

Note that the ADA is a large, unconfined sand and gravel aquifer located in south-central Manitoba. It is heavily relied upon as a source of drinking water and has been extensively developed for agriculture, which requires significant nutrient application. Results of recent research in the region have clearly indicated a high degree of risk to water quality from nutrient-management activities. 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.

As mentioned, the new SABAE-HW model, which is a multi-layer soil version of the Canadian Land Surface Scheme and a horizontal aquifer model, is undergoing prototype testing. A major component of the proposed CWN research work will be to couple a physically-based, one-dimensional nitrogen transport module to the regional SABAE-HW model to quantify the nitrogen budgets of the ADA study site and others within our network of facilities.

*Hydrologic Sciences*

# DROUGHT AND THE LAURENTIAN GREAT LAKES: A PRELIMINARY NOTE

*James P. Bruce*

*Jim Bruce was the first Director of the Canada Centre for Inland Waters in Burlington, Ontario and later served as Assistant Deputy Minister of Environmental Management (Forests, Wildlife, Water, Land) and of the Atmospheric Environment Service (now Meteorological Service) of Environment Canada. He assisted in drafting the 1972 and 1978 Great Lakes Water Quality Agreements and chaired the Economic Commission for Europe's Panel which negotiated the Helsinki Protocol on Acid Rain. Since leaving Environment Canada in 1985, he has undertaken several United Nations agency assignments, helped establish the Intergovernmental Panel on Climate Change (IPCC), chaired the DRI Board of Directors, and has been widely consulted on water and climate change issues. He is an active member of the Forum for Leadership on Water (FLOW).*

## Introduction

Drought conjures up images of dried, caking fields and stunted, wilting plants. It is more difficult to consider drought in connection with the sparkling surfaces of the largest body of freshwater in the world. Yet dry periods do seriously affect water levels and water quality in the Great Lakes in a manner that can have significant economic and social effects.

## The Great Lakes

The central lake in the Great Lakes system is Michigan-Huron, which is sometimes thought of as two lakes but hydraulically consists of one body, all at the same surface water level. It covers 45,500 square miles, or 116,900 square kilometres at average levels. This lake is affected by the outflow from Lake Superior, which has been partially regulated since 1922. Lake Michigan-Huron is a major source of water for the lower St. Clair, Erie, and Ontario lakes and the Atlantic Ocean, through the St. Lawrence River. Its levels are affected slightly by a diversion out of its southern extreme at Chicago (averaging 3200 cfs or 90 cm), which are more than offset by the Ogoki-Long Lac diversions into the Canadian side of Lake Superior (averaging 6000 cfs or 160 cm). It is estimated that the decline in water level due to the Chicago diversion is of the order of a few centimetres.

Figure 1 shows the fluctuation in mean level changes of Lake Michigan-Huron since 1900. Figure 2 shows mean levels calculated from climatic and runoff factors along with estimates

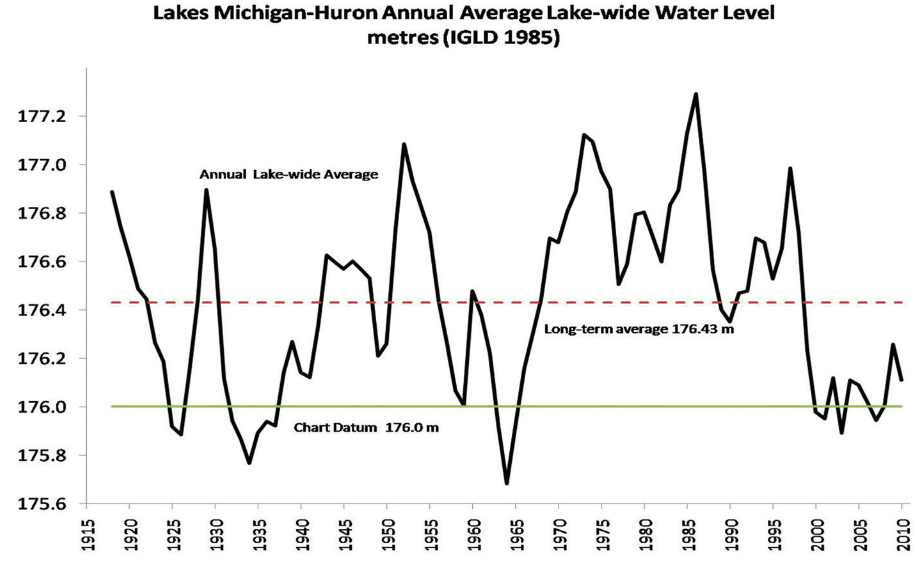


**Figure 1**. The fluctuation in mean level changes of Lake Michigan-Huron since 1900.

of Net Total Supplies (NTS) to the combined lake through precipitation, runoff from the local basin, discharge from Lake Superior, and offset by evaporation from the lake surface.

From Figure 1, levels at or below chart datum (for navigation) were experienced in 1925-1926, 1932-1938, 1959, 1963-1965, and 2000-2008. These large lakes, with depths greater than 305 decametres in places, have enormous heat storage capacity. This means that surface water temperatures lag the seasonal march of air temperatures by many months. This drives the high-evaporation season to fall and winter, when the water is usually much warmer than the outbreaks of cold air sweeping over the basin. In recent decades, more solar energy absorption has taken place during the winter months on Superior and Michigan-Huron due to less ice, leading to increasing surface water temperatures (Austin and Coleman, 2007). This has led to increased evaporation losses, which contributed to the lowering of water levels, especially from 1999 to 2007. Decreased precipitation over Superior also contributed (Assel et al., 2004).

It can be seen from Figures 1 and 2 that there have been a number of episodes of low NTS, expressed as deviations from the long-term average. These low supply periods, which we will refer to as drought, are faithfully reflected in periods of low water levels.

Unfortunately, much of Canada's shoreline development occurred between the late 1960s and 1999, when lake levels and NTS were relatively high. This made the most recent drought, with water levels a half-metre or so below average and often below chart datum for navigation, a serious problem for shore property owners with docks high and dry, for wetland flora and fauna, and for commercial shipping. This situation was exacerbated on the Georgian Bay, on the north-east part of Lake Huron, by the effects of glacial isostatic adjustment causing an upward movement of the land on the shoreline and thus an apparent decline in water levels of 11 cm from 1962 to 2007 near Parry Sound (International Upper Great Lakes Study (IUGLS) under the International Joint Commission, 2009).

These experiences raise questions about the relationship between the more well-documented droughts of the Prairie region under study in the Drought Research Initiative and droughts in the upper Great Lakes basin, the subject of the current IUGLS (2007-2012).

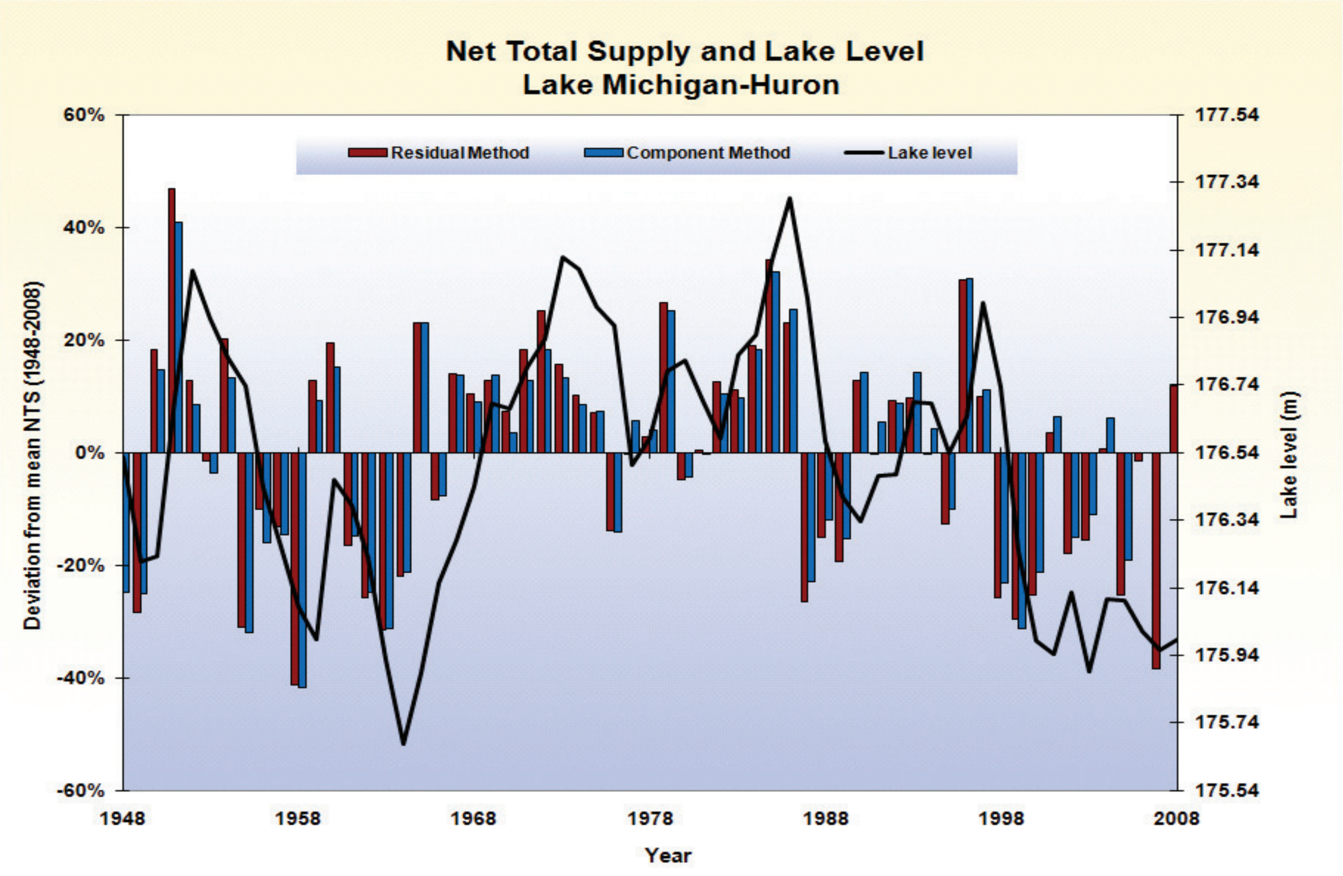


**Figure 2**. Net Total Supplies of water to Lake Michigan-Huron and calculated level effects, 1900-2008.

Do Prairie droughts just move east or are drought periods simultaneous in the upper Great Lakes and the Prairies? Is there a consistent time difference between Prairie droughts and dry spells in the upper Great Lakes? What are the general circulation patterns of the atmosphere that create Prairie and Upper Great Lakes droughts? How much will evaporation rates and lake levels affect snowfall change with rising lake water temperatures? Will climate change forced by greenhouse gases make such dry spells more severe or frequent? Research on these questions gives only some hints at possible answers, but more intensive study is urgently needed. Some is under way in the IUGLS, scheduled for completion in 2012. The current limited understanding is summarized here.

## Prairie Droughts

Research undertaken to place the severe 2001-2002 drought on the Canadian Prairies in a historical context was published in 2007 (Bonsal and Regier). Using regionally-averaged estimates of two drought indices, the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI), the authors concluded that the 2001-2002 drought was severe but was exceeded in duration and probably in severity by the droughts of the 1920s and early 1930s.

The PDSI takes into account both precipitation variations and the effects of evaporation. For the latter, widely available temperature data are used as a proxy. In general, evaporation increases with rising temperatures (Brutsaert, 2006). Estimates by the Great Lakes Environmental Research Laboratory (GLERL) of the U.S. National Oceanographic and Atmospheric Administration (NOAA) show a generally rising trend in evaporation on average over the Great Lakes basin, consistent with trends of rising surface temperatures in Lakes Superior and Huron for the period 1979-2006. The SPI is an index of precipitation only and is more suitable for characterizing agricultural droughts, especially over the growing season. The PDSI is a better index than the SPI for longer-term drought and helps us consider the influence of temperature and evaporation as well as precipitation fluctuations. It is therefore a more suitable index to relate to the water level fluctuation of the Upper Great Lakes, which respond to changes in Net Basin Supply (NBS) over periods of many months and years (see Figure 1).

In Table 1, the times of low water levels (at or below chart datum, the reference level for navigation) and those of low PDSI average values from Bonsal and Regier for the Prairie region (central and southern Alberta and Saskatchewan; southern Manitoba) are shown. Given the geographical distances between the Prairies and Lake Michigan-Huron, the coincidences of timing of drought and low water periods are remarkable from 1920 to the 2000s, although the long lag times involved in recovery of lake levels are evident. In particular, there is a remarkably close correspondence between the two-year-or-longer Prairie drought dates since 1923 and the low levels of Lakes Superior and Michigan-Huron.

| Prairies Severe Droughts (Widespread) | | At or Below Chart Datum (Part of Year) | |
|---|---|---|---|
| **1 Year** | **2 Year** | **Michigan-Huron** | **Superior** |
| 1920-1921 | 1920-1921 | | |
| 1923-1926 | 1923-1925 | 1925-1926 | 1923-1927 |
| 1930-1934 | 1931-1934 | 1932-1938 | 1931 |
| 1937-1941 | 1938-1940 | | 1940-1941 |
| 1946 | | | |
| 1959 | | 1959 | |
| 1962 | | 1963-1965 | 1962-1965 |
| 1982 | | 1977 | 1982 |
| 1988-1989 | 1989-1990 | | 1990-1991 |
| 2002-2006 | 2002-2006 | 2000-2008 | 1999-2005 and 2008 |

**Table 1**. Drought periods (Bonsal and Regier, 2007).

The levels of the Upper Great Lakes integrate the effects of climatic fluctuations, which reflect Net Basin Supplies (precipitation on the lakes plus runoff minus evaporation; NBS) and Superior and Net Total Supplies to Michigan-Huron, which includes NBS plus the inflows to Lake Michigan-Huron through the St. Mary's River. The Bonsal and Regier historical review ends in August 2002. The PDSI values in Table 1 are for the 12-month period ending in August of the indicated year.

In the most recent dry period, below-average NBS to Lake Superior persisted until about August 2007 and levels at or below chart datum persisted until the summer of 2008, as they also did on Michigan-Huron. Thus, in the episode of the 2000s, the Upper Lakes' levels fell at approximately the same time as the drought onset in Western Canada. NBS and the lake levels, however, did not align with the short wetter period in Western Canada from late 2004 to 2006, but remained below average right through to the late 2006-2007 Western Canadian drought, and low lake levels lagged a further year.

This may be due to the importance of evaporation from the water surfaces. Assel et al. (2004) determined that from the beginning of the recent low water level period in 1999, evaporative losses with higher surface water temperatures played a more important role than precipitation deficit, unlike in earlier low water periods.

## Implications for the Future

The question that arises now is whether more severe or more prolonged droughts are likely to occur on the Prairies and in the Upper Great Lakes. In terms of the Great Lakes, the current IUGLS study examines the potential effects of greenhouse gas-driven climate change and adaptive management strategies for these effects. It should be noted, however, that several earlier papers suggest that, according to some climate models and emission scenarios, significant semi-permanent declines in the Upper Lakes' levels (of the order of 1 m) may take place over the course of this century (Mortsch et al., 2000; Kling et al., 2003). On the other hand, a recently published study concludes that the strengthening of the low-level mid-west jet, caused by climate change, will transport more moisture northward from the Gulf of Mexico and thus produce more springtime precipitation into south-western parts of the Lake Superior and Michigan basins (Cook et al., 2008). This may assist in offsetting increasing evaporation.

For the Canadian Prairies and adjacent regions of the United States, Sauchyn et al. (2003) used tree-ring analysis to assess the severity of droughts before the historical record. Their study concludes that more severe and prolonged droughts than those of the twentieth century have occurred in earlier centuries in these regions. Since Global Climate Models, driven by increasing greenhouse gas concentrations, project significantly higher temperatures and only slight increases in precipitation totals, droughts as assessed by the PDSI are likely to increase in intensity and duration. Thus, from both the long-term perspective and current projections of climate change, droughts are most likely to become an increasing problem on the Prairies.

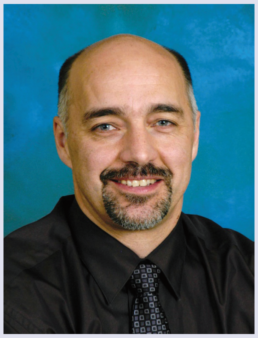
Given the coincidence in timing and, to some extent, severity of low water level anomalies in the Upper Great Lakes and drought indices on the Prairies, these droughts appear to be driven by continent-wide manifestations of internal variability in the climate system. Studies are under way by Bonsal and Shabbar to identify the nature of the atmospheric circulation patterns which contribute to these manifestations. DRI research examining atmospheric patterns over the 1999-2005 period of western drought suggests that precipitation-producing storm tracks differed within this period. Storm tracks were either steered north due to a persistent high over the south-central United States or south of the drought region due to a strong westerly upper-level jet stream shunting moisture from the Gulf of Mexico eastward (DRI Annual Report, 2007). In both cases, this resulted in less precipitation.

Preliminary examination of the main modes of climate variation in the Pacific – El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) – suggests no simple relationship exists between these phenomena and drought conditions from the Rockies to Ontario. The key El Niño 3.4 index was negative from 1998 to 2000 and generally positive from 2002 to 2003. The PDO changed from positive to negative from 1998 to 2001 and fluctuated between positive and negative values from 2001 to 2007. It may be that the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) and "blocking" highs in the western North Atlantic are more conducive to rainy periods over the Great Lakes basin and perhaps even on the Prairies. More intensive study is needed to determine the circulation patterns that are associated with drought conditions from the Rockies to the Great Lakes basin to permit better prediction for improved management.

*Impacts*

# AGRICULTURAL DROUGHT INDICATORS FOR WESTERN CANADA

*Paul Bullock, Manasah Mkhabela, Mark Gervais, Gordon Finlay, and Harry Sapirstein*



*Paul Bullock is an Associate Professor of Agrometeorology in the Department of Soil Science at the University of Manitoba. He teaches classes in Agrometeorology, Micrometeorology, and Soil and Water Management. He has a B.Sc. in Agriculture and a M.Sc. in Soil Science, both from the University of Saskatchewan. He obtained a Ph.D. from the Centre for Resource and Environmental Studies at the Australian National University in Canberra, Australia. Dr. Bullock is interested in quantifying impacts of weather on crop performance, specifically the impacts of growing season weather on Western Canadian wheat and canola quality. He has also assessed agrometeorological risk for crop production on the Prairies and northern Great Plains. Recently, he started a project to develop soil moisture estimates for Western Canada from near real-time weather and satellite data. He has several years' experience in operational crop yield forecasting at the Weather and Crop Surveillance department of the Canadian Wheat Board and explored agricultural applications of remote sensing with Noetix Research Inc.*

## Introduction

Most regions of Canada have experienced drought. The Canadian Prairies are more susceptible to drought mainly because of high spatial and temporal precipitation variability (Bonsal and Wheaton, 2005). Droughts develop slowly and are difficult to quantify in terms of spatial extent and intensity. The success of drought preparedness and mitigation depends on timely information on drought onset, progress, and extent through drought monitoring. Drought monitoring is normally performed using drought indices to provide policy-makers with information on drought severity. In some cases, it can be used to trigger drought contingency plans, if such information is available.

Drought is broadly categorized as meteorological, hydrological, agricultural, or socio-economic (Boken, 2005). Meteorological drought occurs when precipitation over a period of time (e.g., weekly, decadal, monthly, seasonal) falls below normal, while hydrological drought occurs when lack of precipitation leads to shortages of surface water and groundwater. Agricultural drought occurs when a lack of soil moisture negatively impacts crop yield; socioeconomic drought occurs when lack of precipitation hinders the economy and socio-political situation in a region.

A recent review of drought indices (Heim, 2002) illustrates their evolution over the past two centuries from simple approaches based on measures of rainfall deficit to more complex problem-specific models. Detailed descriptions of some drought indices and their limitations can be found in Quiring (2009). Meteorological drought indicators focus mainly on anomalies in the water supply, either as precipitation or soil moisture. Numerous agencies worldwide provide ongoing operational estimates of meteorological drought. In Canada, the Drought Watch programme (www.agr.gc.ca/pfra/drought/index_e.htm) provides regularly updated maps depicting precipitation, temperature, and soil moisture anomalies for the country. Certainly these maps illustrate the severity of meteorological drought in Western Canada, especially in western regions in 2002, as opposed to the more favourable precipitation levels in 2005. Nevertheless, the relationship between meteorological drought and agricultural production is not easy to quantify. Indices that more closely reflect the status of agricultural crops and their productivity potential provide a more accurate depiction of agricultural drought impacts, which in turn provides more accurate information to those organizations that are impacted.

## Drought Index Evaluation

A study was conducted to identify drought indices that correlated closely with Canadian Prairie spring wheat yield and several quality parameters (Mkhabela et al., 2010). Detailed crop and weather data collected from 2003 to 2006 from a series of wheat trials conducted across Saskatchewan and Manitoba were utilized to evaluate the effects of growing season weather on the yield and quality of Canadian Prairie spring wheat. Drought indices were calculated from the meteorological and soil moisture data collected at the study sites and were categorized as water supply, water demand, water balance, and water use (Table 1). The water supply indices used are commonly applied to meteorological drought studies. The most basic moisture variable investigated

**Table 1**. Drought indices and accumulated time periods used in the analysis

| Drought Indices | Abbreviations |
|---|---|
| *Water Supply Indices* | |
| Accumulated Precipitation | Precip[1, 2] |
| Percentage of Normal Precipitation | %Normal Precip[2] |
| Standardized Precipitation Index | SPI[2] |
| *Water Demand Indices* | |
| Reference evapotranspiration as per Hargreaves et al. (1985) | HarETo[1] |
| Reference evapotranspiration as per Allen et al. (1998) | PMETo[1] |
| Standard evapotranspiration as per Hargreaves et al. (1985) | HarETc[1] |
| Standard evapotranspiration as per Allen et al. (1998) | PMETc[1] |
| Potential evapotranspiration as per Raddatz (1993) | PamETp[1] |
| *Water Balance Indices* | |
| Moisture balance (Soil moisture at planting + Precip – HarETc) | HarWBal[1] |
| Moisture balance (Soil moisture at planting + Precip – PMETc) | PMWBal[1] |
| Evapotranspiration Deficit Index (using HarETo and HarETa) | HarETDI[1] |
| Evapotranspiration Deficit Index (using PMETo and PMETa) | PMETDI[1] |
| *Water Use Indices* | |
| Modelled crop water use using HarETo | HarETa[1] |
| Modelled crop water use using PMETo | PMETa[1] |
| Actual evapotranspiration as per Raddatz (1993) | PamETa[1] |

1 Index accumulated over specific growth stages of each wheat cultivar, specifically the vegetative stage from date of planting to date of anthesis (Plan-Anth), the reproductive stage from date of anthesis to date of maturity (Anth-Mat) and the entire growing season from date of planting to date of maturity (Plan-Mat).

2 Index accumulated over monthly periods including May (May), June (Jun), July (Jul), August (Aug), May through June (May-Jun), June through July (Jun-Jul), July through August (Jul-Aug), May through July (May-Jul), June through August (Jun-Aug) and May through August (May-Aug).

at each site was the amount of daily precipitation (Precip) accumulated at different stages of the crop-growing season. Moisture supply was also quantified using monthly percent of normal precipitation (%Normal Precip) and monthly Standardized Precipitation Index (SPI). Monthly %Normal Precipitation values were calculated as the actual monthly rainfall received at the site divided by the monthly long-term normal (1971-2000) from an Environment Canada weather station near each site. Monthly SPI values were calculated by transforming monthly precipitation data at each site using an SPI computer programme available from the National Drought Mitigation Center at the University of Nebraska (www.drought.unl.edu).

The water demand, water balance, and water use indices were designed to quantify water status during the wheat's specific growth phases. A simple water demand index (HarETo) was calculated using the method of Hargreaves et al. (1985), which requires only daily minimum and maximum air temperature (Ta) and latitude as input variables to generate reference evapotranspiration (ETo). A more complex estimate was calculated using the modified Penman-Monteith equation described by Allen et al. (1998; PMETo). This method requires daily minimum and maximum Ta, relative humidity (RH), solar radiation (Rs), and wind speed. Daily standard evapotranspiration (ETc) was calculated by multiplying the daily ETo by a daily crop coefficient (Kc). Kc values were generated using soil moisture and precipitation data to derive actual evapotranspiration (ETa) on a bi-weekly basis for each site and a relationship between Kc and accumulated growing degree days (Finlay, 2006). Daily values of ETc from either the Hargreaves et al. (1985) method (HarETc) or the modified Penman-Monteith

(Allen et al., 1998) method (PMETc) were accumulated over varying periods of time.

The second-generation Prairie Agrometeorological Model (PAMII; Raddatz, 1993) was also used to develop a water demand index. PAMII simulates the interaction between an atmospheric boundary layer that changes twice daily with the weather and a crop-soil boundary layer that evolves through the growing season. Evaporation and transpiration fluxes are determined separately using bulk canopy resistance, soil resistance, and the stability-adjusted aerodynamic resistance. The near-surface vapour density deficit determines the lower atmosphere's capacity to take up water vapour. Potential evapotranspiration (ETp) is the result of this driving force, divided by the aerodynamic resistance. Bulk canopy resistance is primarily a function of crop type and the available moisture in the root zone. The soil resistance is primarily a function of top zone soil moisture. The PAMII model was run with wheat as the crop type and generated daily ETp values, which were accumulated over varying time periods to create another water demand index (PamETp). The PAMII indices provided a comparison to those derived from simpler models to determine if the sophistication of the PAMII model provided improved relationships between meteorologically-derived indices and spring wheat yield and quality.

A combination of variables, including soil moisture at seeding, daily growing season precipitation, and daily ET, were utilized to create a set of water balance indices. The first set of these indices evaluated the accumulated water deficit. The plant available soil moisture at seeding was added to the precipitation accumulated from planting to a specific point in the growing season, minus the ETc accumulated over the same period. Both the Hargreaves et al. (1985) and modified Penman-Monteith (Allen et al., 1998) ETc values were used to create two separate indices of the water deficit, HarWBal and PMWBal, respectively. A variation of this approach is the Evapotranspiration Deficit Index (ETDI; Narasimhan and Srinivasan, 2005), which assesses the ability of actual evapotranspiration (ETa) to keep pace with evaporative demand. The water stress (WS) ratios were calculated as WS = (ETo – ETa)/ETo, where WS is water stress accumulated over a certain time period, ETo is reference evapotranspiration over the same time period, and ETa is actual evapotranspiration over the time period. In this case, ETa was calculated by multiplying ETc by a soil moisture availability coefficient (Ks). Ks values were calculated using the method described by Allen et al. (1998) and differ from soil type to soil type. The values vary between 0 and 1, the former occurring when Total Available Water (TAW) in the soil profile is equal to zero and the latter occurring when TAW is between 50% and 100% of soil water holding capacity. At soil moisture contents below the 50% threshold, Ks was reduced by 0.02 of daily demand for each additional 1% decrease in soil moisture below 50%.

The first set of water use indices used a simple two-layer soil moisture model to determine daily soil moisture availability for the purpose of calculating daily crop water use (WU) or actual evapotranspiration (ETa). The ETo values in the soil moisture model were calculated using both the Hargreaves et al. (1985) and the modified Penman-Monteith (Allen et al., 1998) methods to produce two separate crop WU indices, HarETa and PMETa, respectively. On a daily basis, crop WU was equal to daily demand if the plant available soil moisture was at least 50% of the total plant available soil moisture capacity. At soil moisture contents below the 50% threshold, daily plant WU was reduced by 2% of daily demand for each additional 1% decrease in soil moisture below 50%. When soil moisture reached 0% of available water, plant WU was 0% of daily demand.

A water use index was also calculated from the PAMII model described above (Raddatz 1993). In the PAMII model, minimum and maximum hourly ETa flux (which can be either upward or downward) is calculated daily for each site using the overnight low temperature and 1200 Universal Time Coordinate (UTC) upper air data and the daily maximum temperature and 0000 UTC upper air data. The 1200 UTC data are assumed to apply at sunrise and the 0000 UTC data are assumed to apply two-thirds of the way through the daylight period. A sinusoidal curve is fitted to the minimum and maximum ETa to obtain hourly ETa values, which are then accumulated to derive daily ETa.

Water supply indices were accumulated over monthly intervals from May through August as well as at two-month intervals (May-June, June-July, July-August), three-month intervals (May-July, June-August), and four-month intervals (May-August). These months represent the main growing season for annual crops in Western Canada and coincide with the time of meteorological data collection. The accumulated precipitation and water demand, water balance, and water use variables were accumulated from planting to anthesis (Plan-Anth), from anthesis to maturity (Anth-Mat), and throughout the entire growing season, from planting to maturity (Plan-Mat). A list of all drought indices and accumulation periods is shown in Table 1, along with the abbreviations for each. In total, 72 different drought index accumulation period combinations were assessed. Data were accumulated based on crop development stage because it was expected that a cereal such as spring wheat, for example, would respond differently to weather conditions during the vegetative phase (Plan-Anth) than during the reproductive phase (Anth-Mat). The %Normal Precip and SPI indices, however, were limited to monthly time intervals.

Correlation and regression analyses were used to assess the strength of the relationships between the five different wheat parameters (grain yield, grain protein content, farinograph absorption, dough development time, and loaf volume) and each drought index. The analysis was done separately for each genotype to determine whether responses varied with cultivar. The correlation coefficients (r) generated for each parameter and each genotype were sorted by the absolute value of the correlation coefficient (r) and statistically significant (P<0.05) (r) values were flagged for further investigation. This included determining whether the relationships were more accurately depicted using a linear or non-linear relationship. Since there was no improvement in using non-linear relationships, the linear relationships were utilized. The relationships were also checked to ensure that there was a reasonable distribution of data points across the range of values. The goal was to identify and select those drought indices that were most highly correlated to grain yield and to each of the wheat quality parameters for each cultivar.

## Drought Index Performance

Grain yield for the two wheat cultivars used in the study (AC Barrie, Superb) was negatively correlated only to water demand indices (i.e., PMETc and PMETo), indicating that as water demand increased, either from planting to anthesis or over the whole growing season, grain yield decreased (Figure 1a-b), probably due to water stress caused by depletion of soil water. Grain protein concentration for both cultivars was in most cases positively correlated to water demand and water balance indices (Figure 1c-d) and negatively correlated to water use indices, accumulated from planting to anthesis and planting to maturity. Farinograph absorption for both AC Barrie and Superb was negatively correlated with HarETa for the growing season and from anthesis to maturity for AC Barrie. It was positively correlated with HarETDI accumulated over the growing season for both cultivars as well as from planting to anthesis for AC Barrie and anthesis to maturity for Superb. In addition, farinograph absorption for Superb was negatively correlated to the three water supply indices (i.e., SPI, Precip, and %Normal Precip) for the month of August. In both cultivars, farinograph dough development time was positively correlated with water demand indices (Figure 1e-f) and negatively correlated with water use and water balance indices. In addition, the FarDDT for AC Barrie was positively correlated with PMETDI (a water balance index). Loaf volume in both cultivars was positively correlated with ETo water demand indices and ETDI water balance indices, integrated from planting to anthesis, anthesis to maturity, and planting to maturity. The loaf volume of the cultivar Superb was, however, also negatively correlated to HarETa, PMETa, and PMWBal.

## Best Indices for Agricultural Drought

In total, there were 40 and 52 drought indices with statistically significant correlations to either yield or a quality parameter for the cultivars AC Barrie and Superb, respectively (Table 2). There was a great deal of similarity among the drought indices in terms of correlation to the properties of each genotype. The total number of significantly correlated water supply, water demand, water balance, and water use indices across all grain properties were 0, 19, 14, and 7 for AC Barrie and 3, 24, 18, and 7 for Superb, for a total of 3, 43, 32, and 14 across both cultivars. The low number of significantly correlated water supply indices suggests that meteorological drought indicators do not quantify the effects of agricultural drought well. That being said, they may have performed better if SPI and %Normal Precip could have been accumulated over wheat growth stages as they were for the other indices.

This study has shown that drought indices focusing on evapotranspiration and water balance are most useful for projecting the impact of agricultural drought on spring wheat yield and quality on the Canadian Prairies. Conversely, drought indices that reflect water supply are not useful in this regard. Despite research results indicating the contrary (Hammer et al., 1997), crop water use indices were infrequently significantly

| **Drought Index** | **Genotype** | |
|---|---|---|
| *Category* | *AC Barrie* | *Superb* |
| Water Supply | 0 | 3 |
| Water Demand | 19 | 24 |
| Water Balance | 14 | 18 |
| Water Use | 7 | 7 |
| Total | 40 | 52 |

**Table 2**. Number of statistically significant drought index correlations by category and genotype.

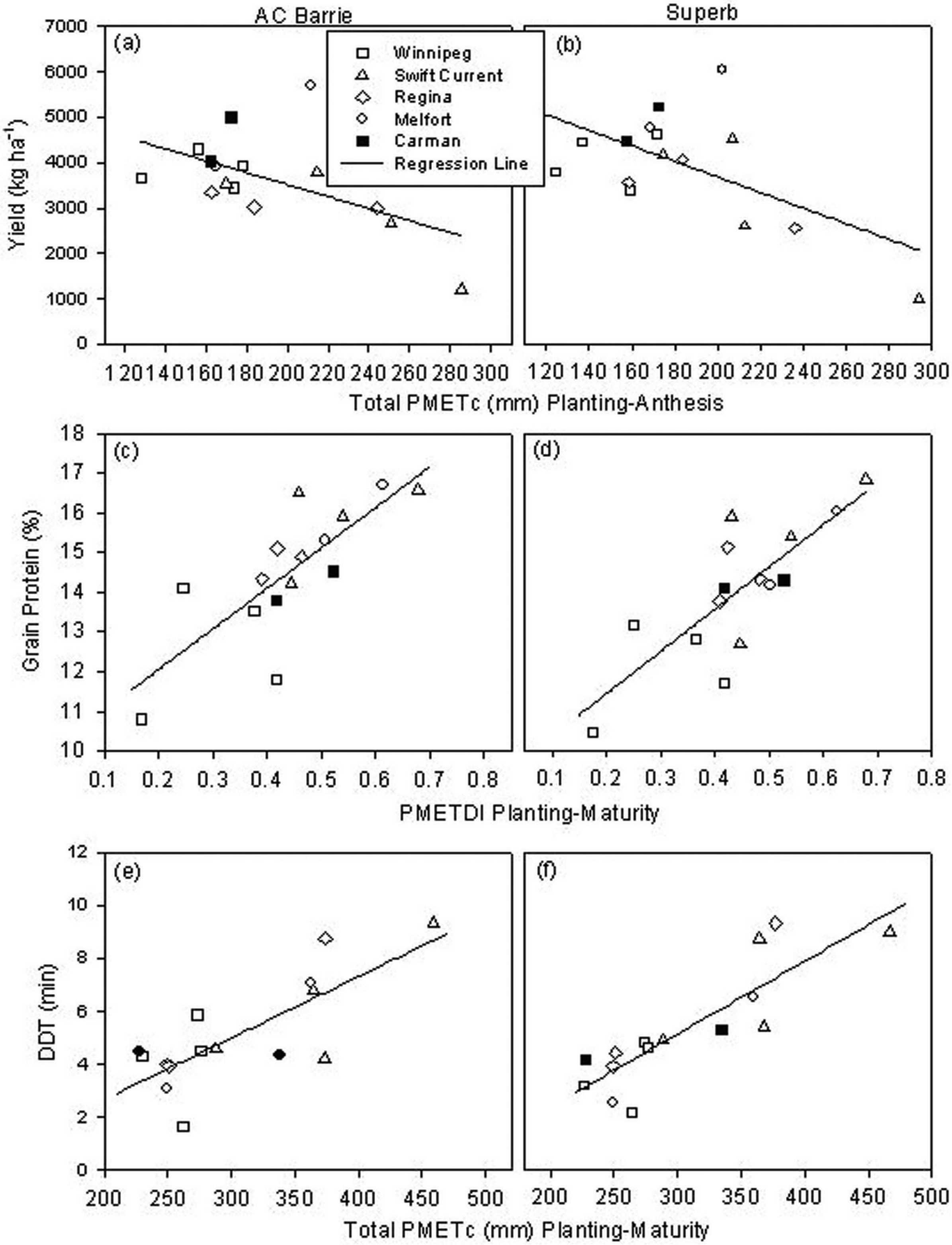


**Figure 1**. Scatterplots showing wheat yield, grain protein, and dough development time relationships to PMETc-Plan-Anth, PMETDI-Plan-Mat, and PMETc-Plan-Mat, respectively, for Canada Western Red Spring Wheat cultivars AC Barrie (a, c, e) and Superb (b, d, f). Abbreviations are detailed in Table 1.

correlated to wheat yield or wheat quality parameters. The results also suggest that drought response was similar between the two wheat cultivars (AC Barrie and Superb), since most of the grain quality parameters measured shared a common drought index or, at least, a set of highly correlated indices.

Drought indices accumulated from planting to anthesis were more highly correlated with wheat quality parameters, followed by those accumulated from planting to maturity and those accumulated from anthesis to maturity. The large number of significant correlations over the planting-to-anthesis time period suggests that it would be possible to generate preliminary estimates of drought impacts on spring wheat yield and quality by mid-season with some confidence. This could provide policy-makers with an early warning to plan and prepare for potential drought conditions.

The indices assessed in this study rely on meteorological data and therefore provide agricultural drought assessment at individual points where weather stations are located. A spatially continuous data source would improve our ability to delineate areas with varying levels of agricultural drought intensity. Current research indicates that vegetation indices derived from the Moderate Resolution Imaging Spectroradiometer satellite images at specific time periods of the growing season are significantly correlated to the yields of Western Canada's major crops. The next step in creating accurate assessments of agricultural drought extent and intensity will be the development of methodology for combining point-based estimates from weather station data with spatially continuous satellite images. This research is currently underway.

# EVAPOTRANSPIRATION MEASUREMENTS CONTRIBUTE TO OUR UNDERSTANDING OF THE EFFECTS OF DROUGHT

*Brian Amiro and the Canadian Carbon Program*

*This research was undertaken by a large number of researchers as part of the Fluxnet-Canada Research Network (2002-2007) and the Canadian Carbon Program (2007-2010; www.fluxnet-canada.ca). These researchers come from universities and government agencies across Canada. Here we focus on a subset of the research undertaken on the Prairies. This involved researchers from Manitoba (Brian Amiro, University of Manitoba), Saskatchewan (Alan Barr and Tianshan Zha, Environment Canada), Alberta (Larry Flanagan, University of Lethbridge), British Columbia (Andy Black, University of British Columbia), and Ontario (Harry McCaughey, Queen's University). These researchers were supported by a large number of students, technicians, and research associates.*

## Why the Research was Undertaken

Human activities have caused an increase in the carbon dioxide concentration in our atmosphere through the release of carbon stored in fossil fuels. Although the land absorbs some of this carbon dioxide, we need to know the amount released, what changes it, and whether carbon uptake will increase or decrease in the future. In Canada, research has been undertaken as part of the Fluxnet-Canada and the Canadian Carbon Program research networks to study carbon transfer between the atmosphere and forests and peatlands. These networks not only study carbon, but also look at the exchange of water vapour and energy. They are all tied to our climate and especially to the water balance of the land. Measurements have been taken at some sites for more than a decade and they allow us to better understand year-to-year variability and the climate trends that influence our ecosystems.

## The Research Methods

The researchers measure the exchange of carbon dioxide, water vapour, and heat using the eddy covariance method. Instruments are mounted on towers above the surface, typically at heights greater than twice the height of the underlying vegetation, to give a spatial average of several hundred metres. The instruments measure the net flux of gases and energy being transferred vertically. The technique calculates the covariance between the vertical wind velocity measured using a fast-response ultrasonic anemometer and the concentration of the gas and the air temperature that is being carried by the wind. Carbon dioxide and water vapour concentrations are measured with an infra-red gas analyzer. Fluctuations in velocity and concentration are sampled several times each second and the net exchange is calculated every 30 minutes. This is done throughout the year to accumulate an annual total.

These measurement stations are located on the Prairies near Lethbridge, Alberta; Prince Albert, Saskatchewan; and Thompson, Manitoba. As part of their contribution to DRI, researchers looked at the exchange of water vapour from the Lethbridge grassland site and the Prince Albert forest sites. The forest sites included areas of mature forest as well as forests that were recently disturbed by fire and harvesting.

The eddy covariance measurements of water vapour exchange give ecosystem evapotranspiration, but the total water balance needs to be estimated in order to understand the local water balance. This requires additional estimates of incoming water through precipitation (rain and snow), losses downward to groundwater through infiltration, and losses laterally through runoff. The left-over water is stored in the soil and in local ponds. Over long periods of many years, we expect the input and output of water to be approximately equal, but in any given year the land could become wetter or drier. This is critical for vegetation, including forests, grasslands, and crops. It also affects the amount of water available for local reservoirs, lakes, and wetlands.

## Summary of the Results

### Grassland

The normal amount of precipitation at Lethbridge is 386 mm per year. The grassland station recorded below-normal amounts in 2000, 2001, 2003, and 2006. Above-average precipitation was experienced in both 2002 and 2005. The Lethbridge grassland site had its lowest evapotranspiration in 2001, following two years of below-average precipitation. This recovered in 2002, likely because of a large rainfall in May of that year. It remained relatively high in subsequent years. The above-average precipitation events in 2002 and 2005 occurred during the growing season, which increased evapotranspiration in those years and also provided water for subsequent years. This also resulted in more plant growth at the grassland site in 2002, 2003, 2005, and 2006. Over the 1999-2006 period, evapotranspiration and precipitation amounts were the same. This would put the ecosystem in a slight water deficit condition once we account for runoff and infiltration.

### Mature Forests

Evapotranspiration was measured at three different mature forest sites near Prince Albert. They consisted of an aspen site, a jack pine site, and a black spruce site. The aspen site is the furthest south and is close to agricultural fields. Precipitation in 2001-2003 was clearly below normal at the aspen site, although higher than normal at all forest sites in 2004-2006. It appears that the aspen site experienced a greater drought than either of the other mature forest sites. Each of these sites received less than 300 mm of precipitation in 2003, far below the normal (approximately 425 mm). An increase in precipitation in 2004 alleviated dry conditions at the pine and spruce sites.

Evapotranspiration at the aspen site was lower in 2002-2004 compared to greater values before and after this period. Cool conditions and recovery from a three-year drought decreased evapotranspiration in 2004. The black spruce site also experienced lower evapotranspiration during this period, whereas the jack pine site did not seem to respond much to the precipitation difference. It experienced a relatively constant evapotranspiration rate, although it was slightly lower in 2002 and 2003 because the jack pine forest was growing on a sandy well-drained soil that is normally short of water, which limits evapotranspiration. The greatest water deficit was recorded at the aspen site in 2003, where evapotranspiration was almost 200 mm greater than precipitation. Surplus water occurred at all the sites in 2004, 2005, and 2006, recharging local ecosystems. All sites were closer to having a neutral water balance in other years.

### Disturbed Forests

The young disturbed forests include a jack pine forest that was harvested in 1994. Evapotranspiration did not change much at this site throughout the period. The site is sandy and well-drained and is close to the mature jack pine site, so it is likely short of water during most years. This would limit the amount of evapotranspiration.

Measurements were made at a forest site that burned in 1998 and at another that burned in 1989. The site that burned in 1989 showed a decrease in evapotranspiration in 2003 compared to 2002 but an increase in 2004 and 2005. The forest that burned in 1998 had the lowest evapotranspiration of all sites but showed a steady increase throughout the period. Evapotranspiration is usually lower in forests with young vegetation because they have less leaf area and do not transpire as much water as more fully developed forests. Vegetation continued to develop at this site throughout the period, increasing evapotranspiration as leaf area increased. Hence, this site did not become water-stressed.

## Implications of the Findings

Evapotranspiration is governed by weather, climate, vegetation, and soil. Our present vegetation has adapted to the normal climate but can be stressed by lack of water in many years. If there are multiple years of water stress, the present vegetation cannot survive and will be replaced by a better-adapted ecosystem. Our measurements show that grasslands, jack pine forests, and young forests are better adapted to short drought periods than mature aspen forests. Young forests, however, are only advantaged while they are young; eventually they will mature. Warmer climates are accompanied by more fire and insect infestations, so we may see an increase in younger forests as the climate changes. Warmer climates also likely lead to drier conditions, even if precipitation amounts do not change. Warmer surfaces have greater evapotranspiration, which causes plants more water stress.

*Impacts*

# IMPACTS OF THE 2001-2002 DROUGHT ON ASPEN FORESTS IN THE PRAIRIE PROVINCES

*Ted Hogg*

*Ted Hogg grew up in Calgary, Alberta and received his Ph.D. in Biology at the University of New Brunswick in 1987, followed by postdoctoral work in Forest Science at the University of Alberta and in Sweden. Since 1992, he has worked at the Northern Forestry Centre in Edmonton as a Research Scientist in the climate change programme of the Canadian Forest Service for Natural Resources Canada. His current research focuses on monitoring and analyzing drought impacts on the productivity, health, and dieback of forests in the Prairie Provinces. He has also been involved in several field experiments aimed at understanding the role of the boreal forest in global cycles of carbon, water, and energy, including Boreal Ecosystem-Atmosphere Study (BOREAS), Boreal Ecosystem Research and Monitoring Sites (BERMS), and the Canadian Carbon Program (CCP).*

## Why the Research was Undertaken

Aspen (*Populus tremuloides*) is the most abundant broad-leaved tree in the Canadian boreal forest. It provides a wide range of benefits to society, including ecological goods and services, and is a major source of wood fibre for the forest industry. Aspen is also the main native tree found in the patchy forests and farm woodlots of the aspen parkland zone along the northern edge of the Canadian Prairies. Since the 1990s, dieback of aspen forests has emerged as a major public concern in the Prairie Provinces and, more recently, across northern Ontario and the western United States. In our early research, we discovered that drought was one of the major causes of these dieback episodes, which has led our research group to wonder if human-caused climate change might be playing a role. According to some models, climate change is likely to lead to a northward movement of dry Prairie-like conditions into the western boreal forest during this century, which could have profound impacts on aspen and other forest types in the region. In response to these concerns, a research and monitoring study called Climate Impacts on Productivity and Health of Aspen (CIPHA) was established in 2000 by the Canadian Forest Service in partnership with Environment Canada and other agencies. The CIPHA study is aimed at the detection of climate-related changes in Canada's aspen forests through plot-based monitoring, tree-ring analysis, aerial surveys, and the development and testing of satellite remote sensing methods. Current CIPHA team members at the Northern Forestry Centre include Ted Hogg, Ron Hall, Michael Michaelian, Trisha Hook, and Eric Arsenault.

## The Research that was Undertaken

A major part of the CIPHA study is devoted to the annual monitoring of changes in aspen forests within 30 study areas spread across western and central Canada, from the southern Northwest Territories to Ontario (Figure 1). Twelve of these study areas were established in the more Prairie-like aspen parkland to provide a more sensitive "early warning" indicator of future climate change impacts in the adjacent boreal forest. The other 18 study areas were located in the boreal forest. In each study area we established six research plots within large blocks of pure aspen forest in natural areas with minimal human disturbance, for a total of 180 plots. At the start of the study, each CIPHA plot contained 25 to 30 trees. They were numbered so that we could keep track of their growth and health each year.

One of the CIPHA study areas is a boreal aspen stand in Prince Albert National Park, Saskatchewan, where a 39-metre-high flux tower was set up in the 1990s to monitor the exchange of carbon dioxide ($CO_2$) and water between the forest and the atmosphere. The tower-based measurements are taken by research groups from Environment Canada (Dr. Alan Barr) and the University of British Columbia (Dr. Andy Black) as part of the Boreal Ecosystem Research and Monitoring Sites (BERMS) research network. Results from the CIPHA study are being used for "scaling up" the knowledge gained from the tower-based measurements to determine whether Canada's aspen forests will continue to absorb $CO_2$ in the future under a changing climate.

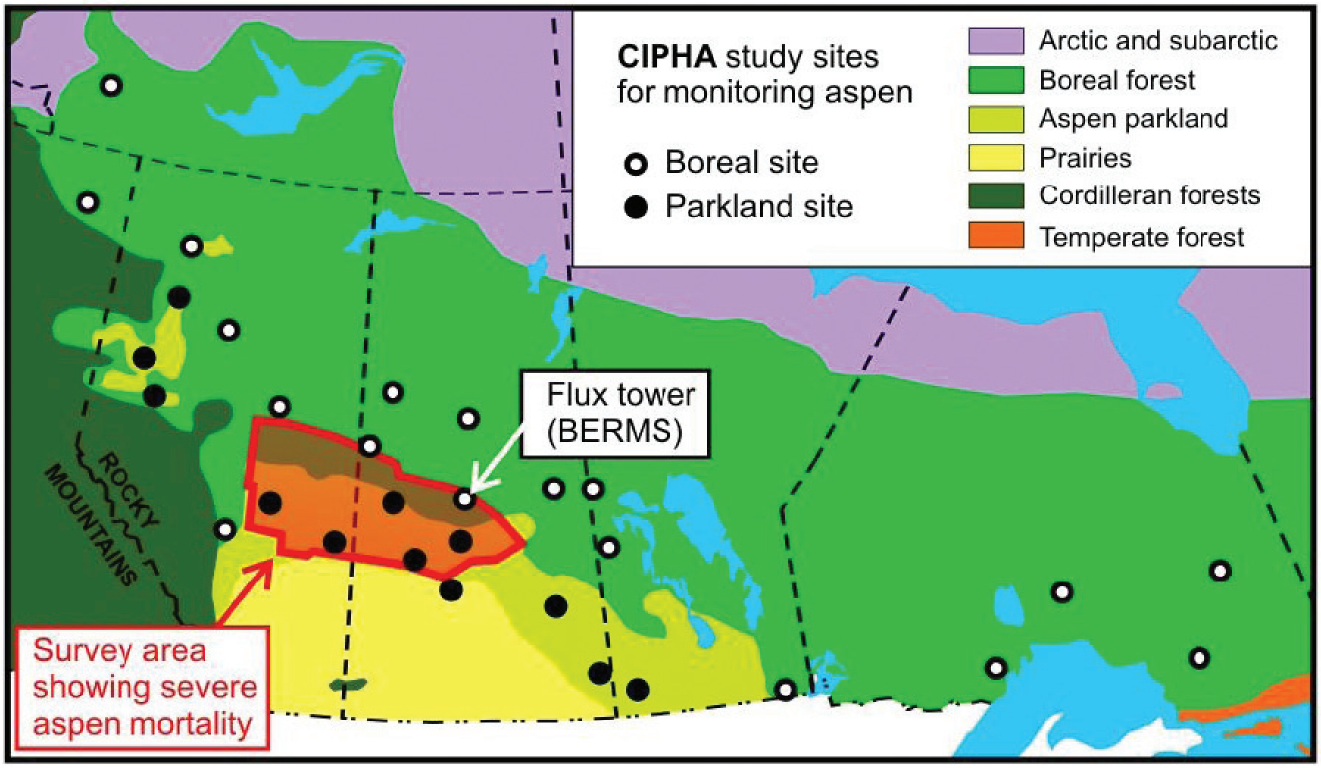


**Figure 1.** Locations of aspen monitoring sites for the CIPHA study.

Every summer since 2000, crews of technical staff and students revisit these plots and record the health of each numbered tree, including damage by insects and diseases, the amount of branch dieback in the tree crowns, how many trees have died, and which dead trees have snapped or fallen. Every four years we also measure the girth and height of each numbered aspen tree and take samples to analyze past tree growth from tree rings. By analyzing the tree rings, we are able to reconstruct the past yearly growth of each tree. From previous research, we have found that aspen form unusually pale-coloured tree rings during years of severe defoliation by insects such as the forest tent caterpillar. This helps determine whether a narrow ring (poor growth) was caused by insects or by climatic events such as drought.

Most of our aspen plots are located in remote forested areas with relatively few weather stations. These stations collect only the most basic weather variables (temperature and precipitation). In order to study past drought effects in these areas, we use a simple Climate Moisture Index (CMI) that can be calculated from the available weather data. The CMI takes into account both the input of moisture from rain and snow and the losses of moisture from evaporation and transpiration (water vapour released from the leaves of trees and other vegetation). Using computer programmes, we are able to apply weather station records and map year-to-year changes in the CMI across the entire study region. This allows us to complete statistical analyses on the effects of past droughts and changes in moisture conditions on the growth, health, and mortality of aspen forests in different areas across the region.

During 2001-2002, an exceptionally severe drought affected the Canadian Prairie Provinces. During this drought, there was an unusual northward extension of dry, prairie-like conditions into the aspen-dominated forests of the parkland and southern boreal forests of Saskatchewan and Alberta (Figure 2). In 2003, we recorded the massive mortality of aspen forests across the most severely drought-affected area of the parkland. The mortality was highly variable, however, which led to a complex pattern of dead, dying, and relatively healthy patches of aspen across the landscape, interspersed with croplands and other vegetation types. We found that, because of this patchiness, the number of CIPHA plots was not large enough to allow us to reliably estimate the drought's impact in terms of how much aspen biomass was killed across the region. To address this, we conducted an aerial survey in 2004 and made additional measurements at approximately 500 temporary ground plots across a 110,000 square kilometre area between Edmonton and Saskatoon. We also expanded the scope of the CIPHA project to include the testing and application of new satellite remote sensing methods for mapping aspen dieback and mortality.

## Summary of the Findings and their Importance

Our research has demonstrated the importance of moisture to the maintenance of healthy and productive aspen forests in Western Canada. The tree-ring analysis showed that periods of decreased growth of aspen are caused mainly by drought and insect defoliation. The analysis also revealed that there have been major regional-scale collapses in aspen growth of up to 50% in the past, notably in the 1960s and from 1978 to 1982, when periods of drought were accompanied by extensive outbreaks of tent caterpillar across the Prairie Provinces.

Based on our yearly maps of the CMI, the drought of 2001-2002 was the worst in over 80 years across the aspen parklands of Saskatchewan and Alberta. Unlike previous droughts, however, it was not accompanied by large-scale insect defoliation. Nevertheless, massive mortality of aspen and other trees was recorded, especially in the most severely drought-affected areas between Edmonton and Saskatoon. Based on collaborative research at the BERMS aspen flux tower site, the drought was less intense but nevertheless had a major impact further north in the boreal forest. Although massive mortality did not occur at this site, the drought led to decreases of 30% to 40% in aspen leaf area and stem growth, which contributed to a transient collapse in net annual carbon uptake by the forest during 2004.

Across the region as a whole, the analysis of CIPHA plot measurements showed that the drought led to a 30% collapse in aspen growth and a doubling of aspen mortality, from about 2.5% to 5% per year. Although there was a return to moist conditions during 2004, aspen mortality has remained unusually high across Western Canada over the past five years. In some stands, nearly all the aspen have died and many dead trees have fallen, creating a more open landscape (Figure 3).

One of the reasons for the ongoing high mortality appears to be the result of damage by wood-boring insects, which also act as vectors for fungal conks and cankers that cause further damage. Annual health assessments show that there was a dramatic increase in damage by these insects, notably poplar borers (*Saperda calcarata*), from less than 10% of stems affected in 2000-2001 to 26% in 2008. In general, the impact of wood-boring insects was greatest in the more severely drought-affected parkland sites. This suggests that the impact of the 2001-2002 drought was amplified and prolonged by interactions with these insects and diseases.

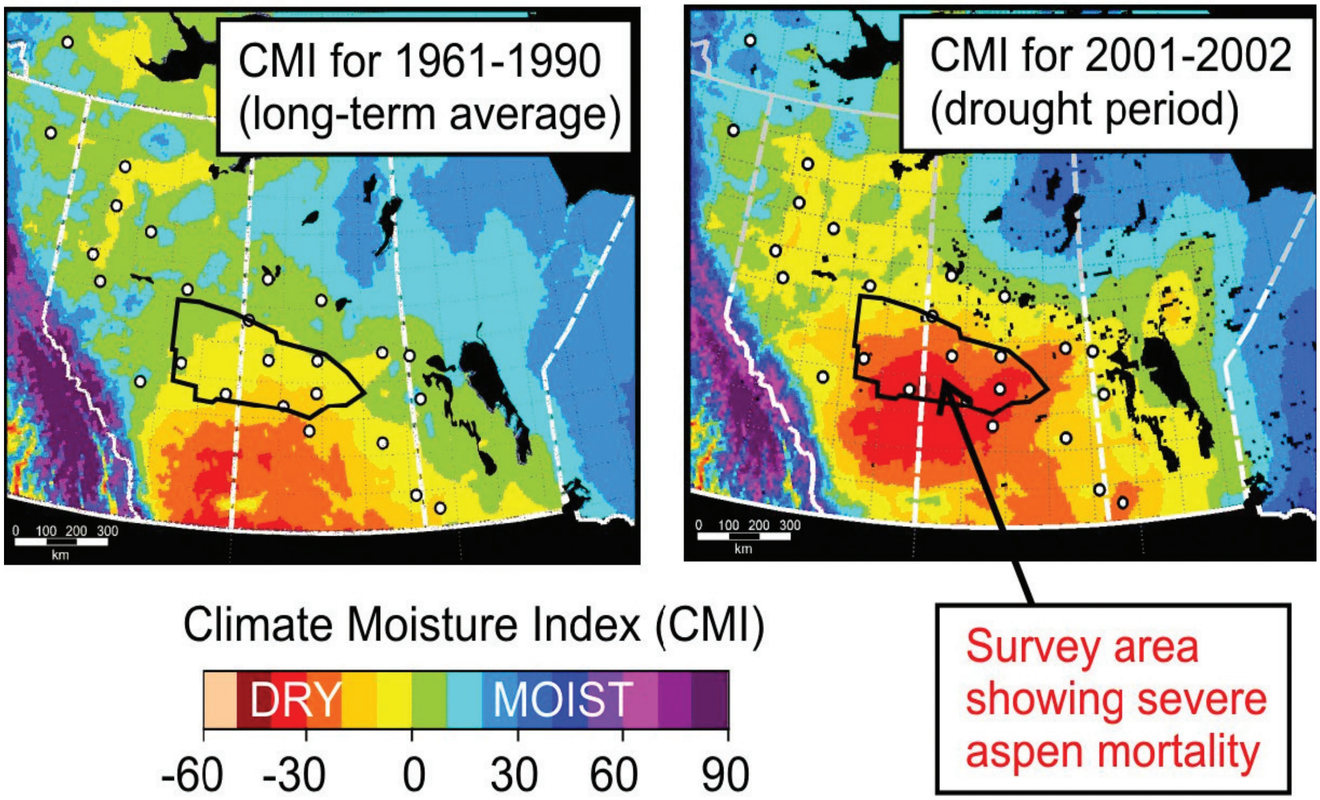


**Figure 2.** Mapping the Climate Moisture Index across the Prairie Provinces and illustrating the severity of the 2001-2002 drought. Maps were generated from interpolations of Environment Canada climate data using the program ANUSPLIN, courtesy of D. McKenney, M. Siltanen, and D.T. Price, Canadian Forest Service.

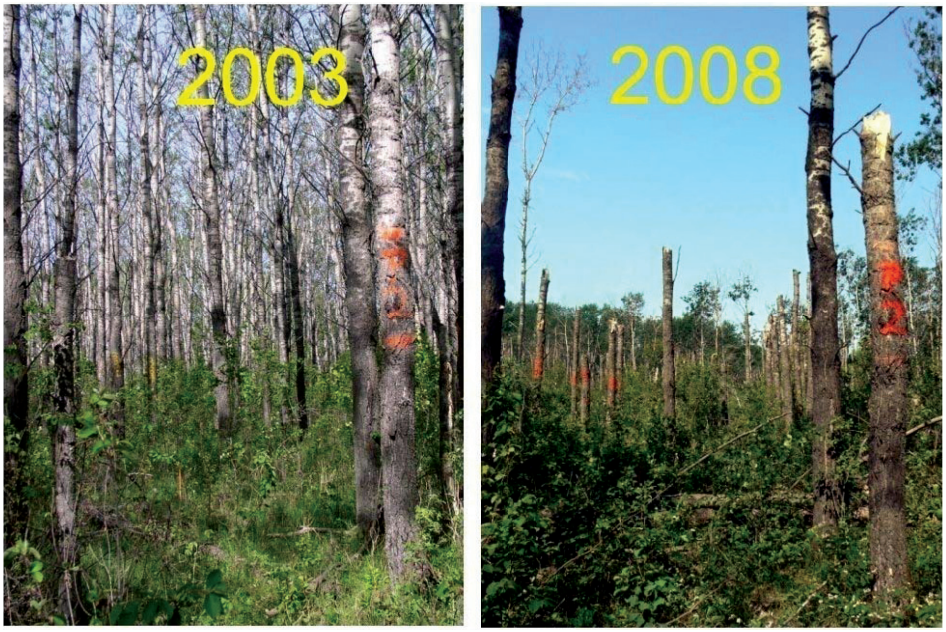


**Figure 3.** Repeat photography of a CIPHA aspen plot at Batoche National Historic Site, Saskatchewan, showing drought-induced dieback in 2003 followed by stand death and break-up five years later. The stand was healthy in 2000, prior to the onset of the severe 2001-2002 drought.

One of the remaining challenges is how to "scale up" our results to estimate the impact of drought across the fragmented landscape of the aspen parkland, which consists of patchy forests interspersed with cropland, grassland, lakes, and other land-cover types. Furthermore, our aerial surveys in 2004 revealed a high degree of patchiness in tree mortality, owing to differences in site moisture conditions (soils and slope/aspect), tree resistance to drought (depending on species, genotype, and age), and a host of other interacting factors. By making additional measurements at about 500 additional aspen plots during 2005-2006, we were able to conduct an analysis showing that there was about 40 million tonnes of dead aspen in the most severely drought-affected survey area. Such measurements are not feasible, however, across the vast area of Canada's forests. Remote sensing methods provide an excellent opportunity for mapping large-scale changes across the landscape, but it is often difficult to relate satellite observations to ground-based measurements. Our ongoing research on this topic is showing encouraging results and should enable our group to develop an operational multi-scale system to meet future needs for more effective monitoring of drought impacts on Canada's forests under a changing climate.

## Implications of the Results

The results from our research on aspen illustrate the risk that drought poses to the sustainability of Canada's forests under a changing climate, especially in regions such as the Prairie Provinces, where trees are already being stressed by a lack of moisture. The knowledge gained from the CIPHA study has enabled the development of models for relating drought severity (e.g., the Climate Moisture Index) to the subsequent impact on forest growth and mortality. These models can then be used to forecast future changes in wood fibre supply and to assess how droughts affect the ability of Canada's forested landscapes to take up $CO_2$ from the atmosphere, which in turn plays a role in determining the rate of global climate change.

Recently, droughts have occurred in other regions such as north-western Ontario and during 2008-2009, when a period of exceptionally severe drought occurred in central Alberta. This poses immediate concerns for these regions' forests. At the global scale, a recent (2010) analysis led by Dr. Craig Allen of the U.S. Geological Survey documented 88 examples of drought- and heat-related episodes of increased tree mortality from all of the world's continents, one of which is the aspen mortality event reported here. The global analysis documented an increasing trend in scientific reporting of such events, but showed that current global monitoring systems are insufficient to determine whether drought impacts on forests are actually increasing due to climate change. In any event, we can be certain that droughts will continue to pose a threat to the forests of the future, so that much can be gained from developing new and innovative approaches for growing trees in drought-sensitive regions such as the Prairie Provinces.

*Impacts*

# THE 1999-2005 DROUGHT IN THE CONTEXT OF THE PALEOCLIMATOLOGICAL RECORD OF PRAIRIE DROUGHT

*Dave Sauchyn*

*Dave Sauchyn is Professor of Geography and Research Coordinator at the Prairie Adaptation Research Collaborative (PARC) at the University of Regina. Dave's research includes the climate and hydrology of the past millennium in Canada's western interior and developing scenarios of future climate and water supplies. As Director of the University of Regina Tree Ring Laboratory, Dr. Sauchyn has collected, with the help of his students, wood from the western boreal and montane forests for the reconstruction of the region's climate and hydrology. Dave is a co-investigator in a five-year multi-disciplinary study of adaptation to climate change in northern Chile and the Canadian plains. He participated in the expert review of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change and was a lead author of Canada's National Assessment of Climate Change, released in March 2008. Dave has been an invited expert witness on climate change in the Canadian Senate and House of Commons and at forums hosted by provincial premiers and environment ministers.*

## Why the Research was Undertaken

Weather stations and water gauges record the data that scientists use to detect, monitor, and predict drought. Despite the quality and number of these records in Western Canada, most of them are too short to capture the decadal and longer-term variability in the regional climate and hydrology. Many causes of climate variation have a periodicity that approaches or exceeds the length of instrumental records. Longer proxy hydroclimate records can provide water resource planners and engineers with a context for reference hydrology to evaluate baseline conditions and water allocations, worst-case scenarios in terms of the severity and duration of drought, and long-term probability of hydroclimate conditions exceeding specific thresholds. They also provide a context for scenarios of water supply under climate change and give us a much broader perspective on the variability of water levels to assess the reliability of water supply systems under a wider range of flows than recorded by a gauge. Equally important is the geographic extent of multi-year periods of low and high flows, including the synchronicity of droughts in adjacent watersheds, that proxy hydroclimate records can reveal.

Tree rings are the preferred proxy for records of climate variability at annual to multidecadal scales spanning centuries to millennia. They are the source of both hydroclimate information and a chronology with absolute annual resolution. Variations in tree ring width reflect conditions that limit seasonal growth. Where tree growth is limited by available soil moisture, standardized tree ring widths correlate with hydroclimatic variables. For example, streamflow data correlate with moisture-sensitive tree ring chronologies, because streamflow and tree growth have a similar muted response to episodic inputs of rainfall and snow melt water. When watersheds are wet (dry), streams rise (fall) and tree growth is enhanced (suppressed). Hydrological peaks are usually underestimated by tree rings; other growth factors become limiting when there is sufficient soil moisture. Proxy records do not provide precise volumes of streamflow, yet they capture the timing and duration of periods of high and low flow. Tree rings are an especially good indicator of drought because dry years produce narrow rings.

## The Research that was Undertaken

In the University of Regina Tree Ring Lab (www.parc.ca/urtreelab), we collected old wood from more than 100 sites to reconstruct moisture and streamflow variability over the past millennium. Nearly all of these collections are from open-canopy forests on ridge crests, south- and west-facing slopes, and/or rapidly drained soils. At these dry sites, tree growth is limited by available soil moisture; our tree ring chronologies are proxies of summer and annual precipitation, soil moisture, and runoff. This network of tree ring chronologies extends across the western boreal and montane forests of Alberta, Saskatchewan, and the Northwest Territories. Our samples are mostly from the northern and western margins of the drought-prone Prairie ecozone, but also from island forests surrounded by Prairie, such as the Cypress Hills of Alberta and Saskatchewan, the Bears Paw Mountains and Sweet Grass Hills of Montana, and the Missouri River Valley in North Dakota.

We built a network of tree-ring chronologies and reconstructed available annual and seasonal moisture to provide a longer view of the western interior's hydroclimate and improve our understanding of drought's frequency, severity, and duration. We sampled more events than recorded at weather stations. Since this information has implications for the management of water, soil, and vegetation resources, it has been sponsored by many government agencies and water utilities, including federal and provincial ministries of agriculture, environment, and natural resources, Manitoba Hydro, and EPCOR Water Services.

Over the past several years, our research focused on the tree ring reconstruction of streamflow and drought in the Saskatchewan River Basin. The eastern slopes of the Rocky Mountains in southern and central Alberta are the source of the North and South Saskatchewan Rivers and also contain some of the oldest wood in Canada. We have sampled 600-year-old Douglas fir trees and 800-year-old limber pine in the region. Dead trees with a similar number of annual rings can be found intact where they have not been in contact with wet ground (i.e., lying on solid rock). If the living and dead trees were growing at the same time for at least a few decades, we find the common rings and transfer calendar years from the living to dead trees. This cross-dating process enables us to construct tree ring chronologies that approach 1,000 years in length. For the period of instrumental weather and water observation, we develop a mathematical relationship between the standardized tree ring widths and hydroclimatic data from nearby gauges. This statistical model is then applied to the tree ring data to determine the relative water levels each year for the entire tree ring record.

## Summary of the Findings and their Importance

At dry low-elevation sites in the upper reaches of the Saskatchewan River Basin, tree growth is closely related to the availability of water and therefore to surface water levels and indices of drought. This relationship has enabled us to reconstruct the flow of the North and South Saskatchewan Rivers and their major tributaries over the past 600 years from living trees. As we cross-date samples of living and dead wood, we are extending these reconstructions to 1,000 years. In Figure 1, the reconstructed annual flow of the South Saskatchewan River at Medicine Hat is plotted for the past 600 years using blue and red bars to depict positive and negative departures from the mean flow, respectively. Sequences of low flows (long red bars) are evident during the dry years of the 1920s and 1930s, 1980s, and 1999-2002. These well-documented historical droughts are thus captured by the tree rings. These droughts are not uncommon. Many droughts of similar severity and duration are evident in the full tree ring reconstruction. The most prolonged droughts (where many consecutive red bars are not interrupted by long blue bars) predate the direct observation of weather and water.

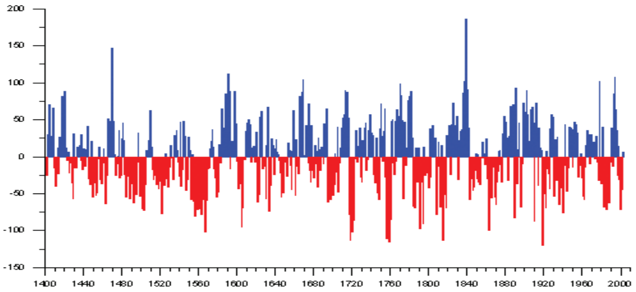


**Figure 1**. Reconstructed annual flow of the South Saskatchewan River at Medicine Hat, 1402-2003 (from Axelson et al., 2009). The annual flow is plotted as positive (blue) and negative (red) departures from the mean flow (the vertical axis represents mean annual streamflow; units are cubic metres per second (m$^3$ sec-1).

These proxy water records reveal much more than just a larger range of extreme conditions. They capture the tempo of natural climate variability and the near-regularity of wet and dry cycles at certain frequencies. They show that the hydroclimatic regime periodically shifts from predominantly interannual variation to intervals with extended wet and dry spells. This knowledge of long-term climate variability contributes to our understanding of the climate system at scales that exceed the length of instrumental records. The longest and most intense droughts and the factors that cause them reoccur so infrequently that a pre-instrumental paleoclimate perspective is required to validate the modelling and prediction of these events.

## Implications of the Results

The results of this research have important implications for understanding and preparing for climate change and increasing resilience and adaptive capacity to ensure the sustainability of livelihoods and ecosystems. The natural hydroclimatic variability captured by tree ring records underlies the trends imposed by the impacts of climate change on water supplies. The Prairies have Canada's most variable hydroclimate. This natural variability must be known if we are to detect the effects of climate change. As global warming amplifies natural variability, more extreme climate conditions, including severe drought, are expected. Most climate change impact assessments suggest that the greatest risk to the Prairies is the challenge posed by more severe, frequent, or prolonged drought. Our capacity to withstand and prepare for water scarcity has developed in response to the droughts that have occurred since the Prairies were settled for agriculture. Greater adaptive capacity will be required if future drought conditions are more severe or prolonged than those previously experienced. Significant adaptations to water management practices and policies are required, starting with scientific knowledge extending beyond instrumental records and a scale at which water supplies seem secure and stationary, to the longer view provided by paleoclimate records and modelled projections.

# FACILITATING DROUGHT DATA ACCESS, MANAGEMENT, AND ARCHIVING THROUGH THE DRI DATA MANAGEMENT FRAMEWORK

*Phillip Harder and Patrice Constanza*

*Phillip Harder is the Drought Research Initiative (DRI) Data and Information Manager at the University of Manitoba. He has been involved in developing the DRI Data Legacy, provides data support to the Network, and contributes to Drought Early Warning System (DEWS) exercises and analysis of the hydrologic aspects of drought. Phillip Harder graduated from the University of Saskatchewan with a B.Sc. in Geography in 2008.*

*Patrice Constanza is the Drought Research Initiative Data Access and Integration (DAI) Data Manager. Working at McGill University in Montreal, Patrice has been involved in developing DAI since 2006. Through web services, he provides a wide range of data to the users of supporting partners (Environment Canada, Global Environmental Climate Change Centre, Ouranos and DRI). Patrice took his M.Sc. in Climate Change from the University of East Anglia (U.K.) in 2002 and his B.Sc. in Meteorology from the University of Reading (U.K.).*

## Introduction, Background, and Motivation

It has become clear to the scientific community that in order to have a successful project, a central infrastructure must be developed. This central infrastructure must allow access to a wide range of data and manage interactions between scientists and the data. This must be put in place before any science can be done.

From the beginning, the DRI project recognized that such an infrastructure is essential to organize and discover data pertaining to the 1999-2005 drought. Without a suitable infrastructure, data would have been very difficult to collect and manage effectively. We may not even have known of the drought's existence.

A useful analogy for understanding the data infrastructure is a neuronal network in which each scientist (a neuron) allows other scientists (other neurons) to know of the existence of a certain dataset. By increasing the number of linkages and tying them into a central location (the brain), the information can then be provided to the rest of the community (the body) in a much more efficient way.

In order for DRI to fulfill its research objectives in an efficient, coordinated, and timely manner that avoids duplication, a data management system was required. The research focused on the 1999-2005 drought. The data necessary to study drought came from many non-DRI sources.

The purpose of DRI data management was to support the research network by providing the necessary infrastructure to help DRI scientists perform their work. This infrastructure includes data access, data management, and data archiving. The data management infrastructure also provides expertise on a wide range of data that DRI scientists need but lack the time or knowledge to collect themselves. This expertise gives scientists more time to analyze data and helps them integrate their results in more user-friendly ways for their own benefit as well as for that of the public (with the use of Google Earth, for example).

Additionally, DRI data management facilitated the long-term storage of DRI-related datasets.

A critical aspect of DRI concerns access to information in terms of a wide variety of variables that can be used to characterize drought. The sheer volume of data related to this topic and their associated issues requires staff with the necessary experience and skills. This ensures that investigators can focus on their work exclusively without encountering as many data issues.

## Methodology

In order to achieve those objectives, the DRI data management team members created and developed two systems. The DRI Data and Information System directly supports the DRI network and provides investigators with solutions to data issues, while the DRI Data Legacy System was developed in response to a Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) requirement to archive and gather publicly available data through funded projects.

## DRI Data and Information System

The DRI Data and Information System acts as an interface, facilitating the DRI user's access to data. The research endeavour focuses on the 1999-2005 drought. Since DRI only began in 2005, the data necessary for this drought study had to be gathered from many non-DRI sources. The data system developed by the DRI data management team provides a range of services for accessing the data using various platforms.

### Central Servers

The Data Access and Integration (DAI) group developed and maintains the central servers, which are an integral component of the DRI network, at McGill University. The system consists of two web servers that host the DAI web services, which are directly linked to the DRI webpage. The two servers allow flexibility during planned or unplanned shutdowns and ensure reliability for users. A series of disc arrays with 40TB of space are also used to store the data.

There are two ways to store large datasets. The first method is to use a tape library. The advantage of this system is that it accepts a large amount of data, but it is inconvenient: data retrieval is quite slow and tape libraries are expensive to purchase and maintain. The second option is the use of disc arrays, which is a more traditional way to store small amounts of data. Due to technological advances, this option is being used more frequently to store large amounts of data. The data retrieval speed is significantly faster than that of a tape library.

The disc array option was chosen because the retrieval speed is of utmost concern to users, which in turn encourages more frequent use of the data infrastructure. Even if a system is cutting-edge in every aspect but speed, users will prefer other means of data retrieval or may omit the data from their research altogether.

DAI uses a computational server with four central processing units to allow pre-processing and post-processing operations on the data. This infrastructure was chosen due to time considerations, as four CPUs allow DAI to pre- or post-process several data requests at the same time without slowing the whole system down. In addition, it allows multiple users to work on the system at once without interfering with one another.

The combination of these three elements (web servers, storage space, and computational capabilities) allows DAI to provide large-scale datasets produced by regional models, global models, and reanalyses to a wide range of users. The metadata for these datasets can be quickly and easily accessed and searched for using McGill University's computers and the DRI website.

### Local Computer Systems

All investigators have their own systems and act as independent components of the DRI research programme. Many create value-added datasets and products within their own groups. Following agreements with CFCAS, each investigator has to make his or her datasets and products available to the DRI community and the general public. For that purpose, the DRI data management team has developed a semi-automatic online database, a component of the DRI Data Legacy, in which an investigator may upload his or her metadata, thereby making it widely available. Given the large investment of time and effort required to collect these data and the desire to ensure that they are of the best possible quality, a time lag of up to one year is allowed to enable investigators to verify, analyze, and publish results before making them public.

### DRI Website

The DRI website provides a list of links to the relevant drought data sources within and outside the DRI data system. It also hosts metadata for browsing and a selection of data for download.

The DRI vision for data management combines the three aforementioned platforms (central servers, local computer systems, and the DRI website) to deliver integrated services to DRI investigators, the drought data user community, and the public. Figure 1 shows the relationship among these platforms, data suppliers, and data users.

| Archive | Datasets | |
|---|---|---|
| Data Access Integration | • Global Climate Models (CGMC2, CGMC3, HadCM3, and ECHAM4)<br>• Regional Climate Models (CRCM and ARPEGE)<br>• NARR | • NDVI<br>• Environment Canada observation station data |
| Investigator Archives | • Field data (St. Denis, Saskatchewan; West Nose Creek, Alberta; Kenaston soil moisture mesonet, Saskatchewan; Assiniboine Delta Aquifer, Manitoba; and crop agro-meteorology, Saskatchewan and Manitoba)<br>• Observational data (upper air, lightning, meteorological, snow cover/surveys, streamflow, soil moisture, wetlands, groundwater, soils, and Sea Surface Temperatures)<br>• Gridded meteorological data (CRU TS 2.1, ANUSPLIN, and CANGRID)<br>• Indices (SPI, PDSI, CMI, and teleconnections)<br>• Model simulations (VIC, CRHM, PAMII, SABAE, GEM, MESH, and CLASS) | • Satellite data (GRACE, MODIS, and AVHRR)<br>• Water and energy budgets<br>• South Saskatchewan River Basin Project datasets<br>• Environment Canada weather radar<br>• Canadian Precipitation Analysis<br>• CPC Merged Analysis of Precipitation<br>• GPS-derived precipitable water<br>• Surface Radiation Budgets cloud data |
| DRI Website | • Alberta/Saskatchewan/Manitoba groundwater data<br>• 1-km land surface grid<br>• Hourly Environment Canada meteorological data | • Alberta Agriculture meteorological data<br>• Environment Canada adjusted and harmonized Canadian climate data |
| DRI Data Legacy | • Prairie groundwater data<br>• Kenaston soil moisture mesonet<br>• Gridded land surface dataset<br>• VIC model input/output-derived SMAPI<br>• PAMII model input/output<br>• CRHM-modelled Prairie and wetland hydrology<br>• 1960-2006 hourly meteorological data at select Prairie locations | • Eddy correlation data<br>• Gridded SPI and PDSI<br>• Census agricultural region yield deviation<br>• Growing season NDVI<br>• Environment Canada Prairie radar data<br>• GRACE satellite data |

**Table 1.** Summary of DRI data holdings.

Table 1 outlines examples of the data and where they fit into the DRI data structure, including the DRI Data Legacy, while Figure 1 shows the linkages employed by data users to access stored datasets. If the information needs of a particular user cannot be met with the metadata or the software and connections available through the website or DAI, then the Data and Information Manager will seek out a solution to the problem or will refer the user to someone who can help him or her access the data.

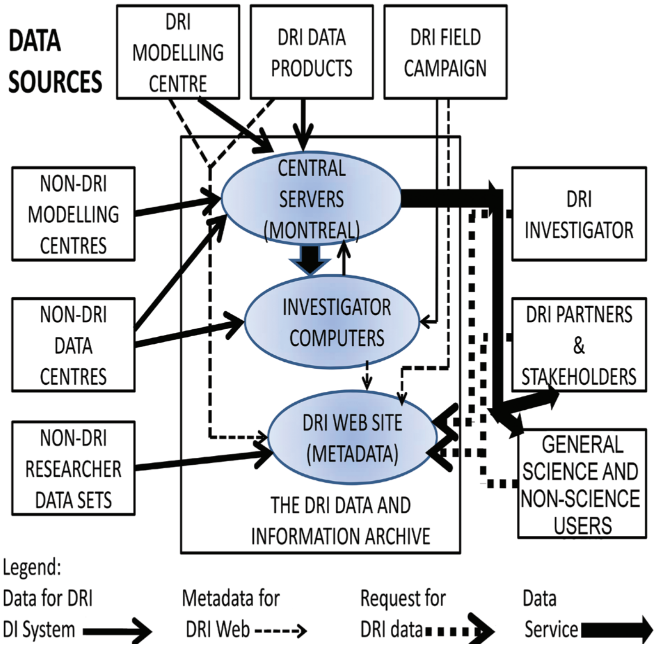


**Figure 1**. DRI Data and Information System.

## DRI Data Legacy System

DRI has collected and generated a large amount of data relating to drought that is not currently readily available to decision-makers. In order to meet the needs of drought information users, an integrated data system for consolidating regional information about drought is being developed. The DRI data legacy will not only serve the needs of the research community, but will also provide governments and the public with better access to information about drought phenomena.

The DRI Data Legacy (Figure 2) includes a metadata information system that may be coupled with an easy-to-use interface such as Google Earth, which users can browse for relevant drought data.

The centralized metadata storage will link to both centralized and distributed data systems. The goal is for users to find relevant drought data tailored to their location of choice. Since not all data are available across the region, a system that can selectively provide information where it is valid would be a considerable step forward in providing drought information. Metadata and data are currently being collected through the DRI website. The metadata formats will be consistent with ISO 19115:2003 standards.

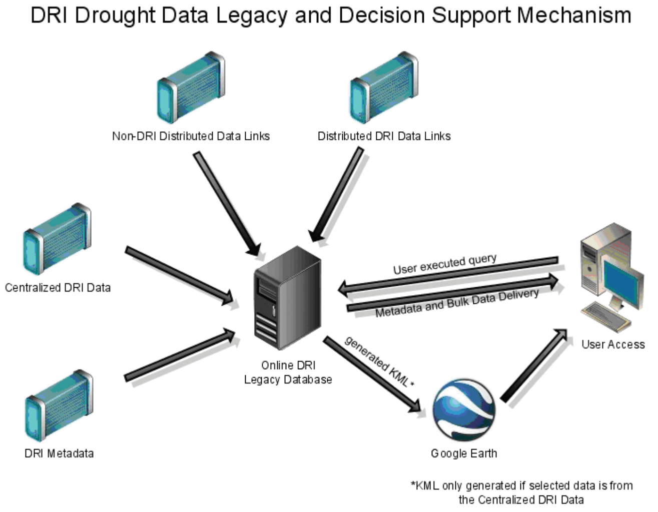


**Figure 2**. DRI Data Legacy.

## Implications of DRI Data Management

DRI Data Management has had a significant impact on the success of the DRI network. The support given to DRI investigators and collaborators in terms of accessing datasets has spared them considerable time and expense. Additionally, the data legacy and the DAI system will allow the DRI network to have a continuing impact by providing access to a high-quality data archive that is relevant to the study and management of drought. DRI represents and participates in broader drought data initiatives, including the Group on Earth Observations (GEO). GEO and DRI have integrated some of the common data-related aspects of their work through, for example, the "Impacts of drought" sub-task (GEO Task WA-06-02b). A spin-off has been the inclusion of the DRI Data Legacy as a decision-support application (in response to a June 2009 call for proposals on Societal Benefit Areas (Water, Agriculture, Weather and Climate) that are of importance to GEO).

Thanks to these efforts, DRI activities will have an impact even after the network officially concludes its work. In addition, DRI's data management work and collaboration with other organizations (Ouranos, Global Environmental and Climate Change Centre, and Environment Canada) have facilitated improved data accessibility for the benefit of researchers, including those not directly involved in DRI.

*Data Legacy, Outreach, and Policy*

# DROUGHT PREPAREDNESS AND INFORMATION ASSESSMENT THROUGH TABLETOP SIMULATIONS

*Jeremy Pittman, Nancy Lee, Phillip Harder, Tom Harrison, and Harvey Hill*

*Jeremy Pittman is a Climate Change Adaptation Specialist with the Saskatchewan Watershed Authority and Saskatchewan Ministry of Agriculture. His current projects investigate ways to improve extreme climatic events preparedness in the context of changing conditions, with a focus on drought and excessive moisture. He has an M.Sc. in Geography from the University of Regina, where he studied the vulnerability of rural and indigenous peoples to climate change and variability.*

## Research Rationale

Preparedness is important for reducing vulnerability and increasing resistance to one of the most enigmatic natural disasters, drought (Wilhite, 1993; 1996). The Drought Preparedness Partnership (DPP) project aims to better understand the ways in which formal institutions respond to and plan for drought in order to gain insights into possible drought preparedness augmentation strategies. A major component of the DPP is to move institutions away from their typical disaster management approach and create pathways for institutionalizing a risk management approach. Proactive impact mitigation planning to minimize risk is fundamental to the risk management approach but overlooked in the disaster management approach. Here we explore the value of information in the drought preparedness process, how it is used, and how its use could be improved. Since we anticipate more frequent and severe droughts that are likely to require proactive management, institutionalized drought-related risk management and improved information could go a long way in preparing institutions for future drought conditions (Wilhite, 1996).

## Research Description

Through tabletop exercises, the DPP wishes to answer the following questions: how can institutions address past weaknesses in their drought preparedness? How can information be enhanced, in terms of quality, timeliness, and accessibility, to increase drought preparedness? This is accomplished through two subprojects (Figure 1), the Drought Preparedness Assessment (DPA) and the Drought Early Warning System (DEWS). The DPP and DEWS were initiated through a collaboration between DRI and Agriculture and Agri-Food Canada (AAFC).

At the DPP workshops, the DPA and DEWS operate successively through a tabletop exercise based on the activity structure shown in Figure 2, an important tool for assessing and increasing disaster preparedness (Homeland Security Exercise and Evaluation Program, 2007). The DPA portion focuses on the policy and operations side of the partnership, attempting to identify gaps in preparedness. The main capabilities highlighted and assessed within the DPA portion of the exercise are policies and plans (drivers and barriers), resources (staffing and budget), information (availability, quality, and timeliness), and adaptation (proactive activities).

In the DPA portion, participants are walked through a simulation of a past drought (the 2001-2002 drought) and are invited to discuss their institutions' responses, or lack thereof, in relation to the aforementioned capabilities. Discussion periods take place at strategically placed breaks throughout the exercise. Drought preparedness is characterized qualitatively through discussion and quantitatively, in terms of the pre-2001-2002 drought, with a questionnaire. Participants are then moved through a hypothetical future drought scenario and, using insights gained from past experiences now fresh in their minds, are asked how their institutions might respond, how future responses could be improved, and what immediate actions can be taken to mitigate future drought impacts and increase preparedness. Following the future scenario, a more in-depth investigation of the role of new information in drought preparedness is conducted in the DEWS portion.

The DEWS portion investigates how current drought information is used, what information and experimental data products are useful, and how further research may address the previous questions. Participants are presented with biophysical drought-related information, followed by a discussion regarding the timing, skill, and scale required for information to be useful in decision-making. The goal is to facilitate a drought information dialogue between information users and researchers, leading to more responsive research and informed utilization of information. It strives to improve drought management, planning, and response initiatives by incorporating scientific information. The DEWS forum allows users to discuss their data requirements and applications and researchers to explain the scientific significance of various drought-related data. In doing so, the DEWS portion attempts to address the research-operations knowledge gap that exists between scientists and decision-makers.

## Research Results

The first DPP workshop was held in Saskatchewan focused on provincial agencies. Participants from the Saskatchewan Watershed Authority, the Saskatchewan Ministry of Agriculture, SaskPower, and Saskatchewan Emergency Management Organization were brought together to discuss drought preparedness in the province. A similar workshop held in Manitoba drew on experts from Manitoba government departments in agriculture and water resource management.

Participants perceived that overall provincial drought preparedness improved when compared to its status before the 2001-2002 drought (Figure 3). Major improvements were carried out in terms of the availability, quality, and timeliness of information. This is significant because information was ranked as the most important capability for increasing drought preparedness. Resources, in terms of budget and staffing, were perceived as the only capabilities contributing to decreasing drought preparedness. This capability was ranked the least important, however, in terms of improving drought preparedness. Drought preparedness related to policies and plans increased most dramatically in terms of drivers and less significantly in terms of barriers. Adaptation in terms of proactive planning, although still not necessarily adequate for drought preparedness, was also perceived as significantly improved. Policies, plans,

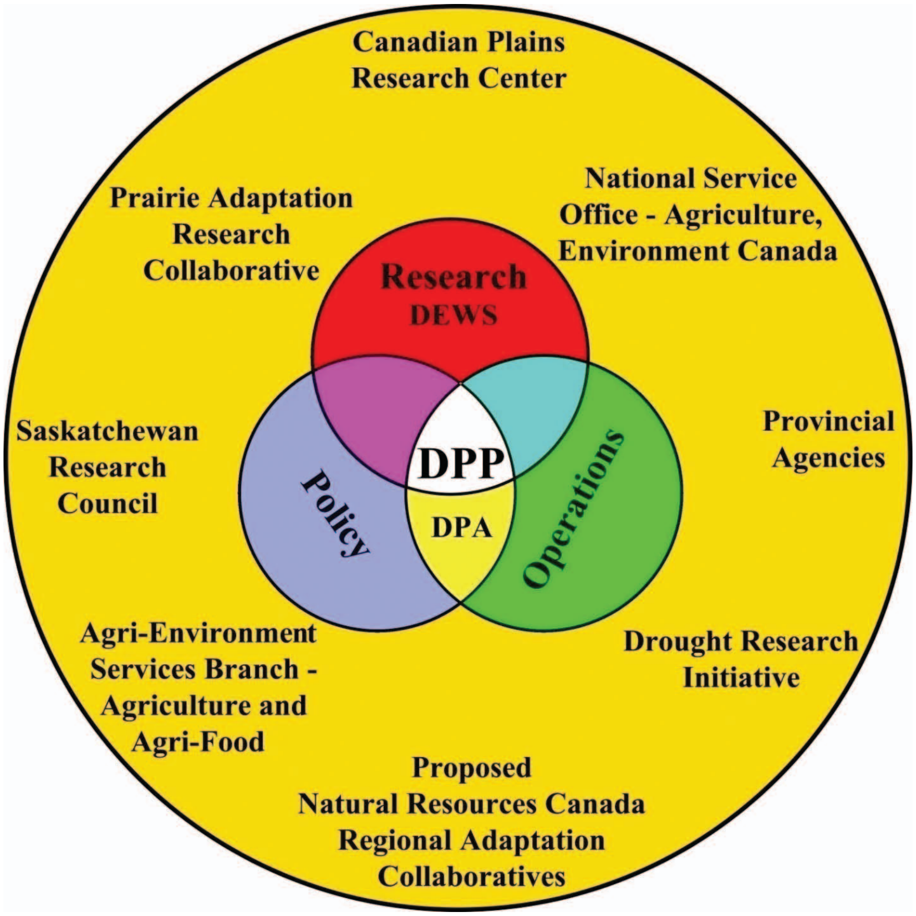


**Figure 1.** Drought Preparedness Project framework.

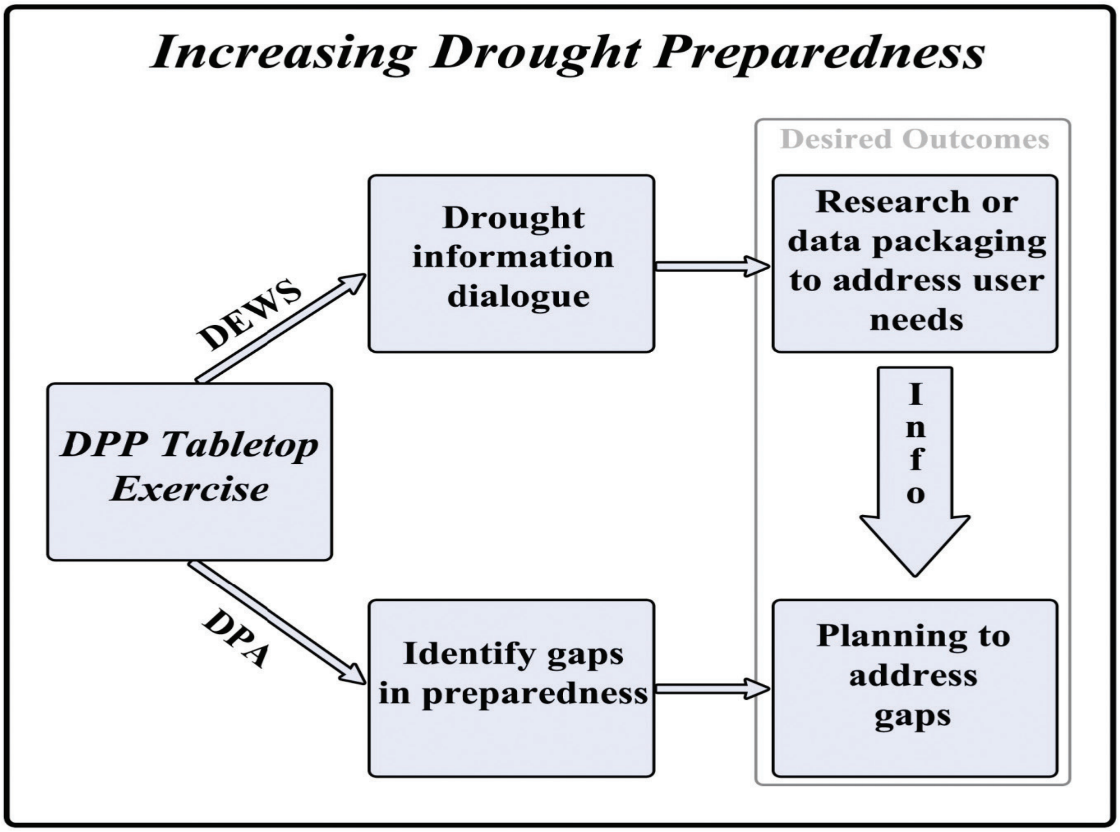


**Figure 2.** Drought preparedness augmentation approach.

and adaptation were ranked of equal importance for improving drought preparedness.

With information availability designated as the most important capability for increasing drought preparedness in the DPP project, the benefits of the DEWS project are highlighted. Several observations from the DEWS dialogue included the fact that all available information is valuable to decision-making processes; improved temperature and precipitation estimates/predictions are particularly valuable as they are most easily understood; there is a need for more supporting information to properly interpret data; 70% to 80% data accuracy is required for most users' needs; and information demands differ throughout the year depending on the economic/operations sector.

The preliminary conclusions of the DEWS exercise are that the greatest barrier for the use of drought information is how to properly understand and use the data. End users need to be properly educated and made aware of the potential uses and limitations of the data.

Three primary improvement areas were identified by participants: more proactive planning in terms of drought response is necessary; resource allocation plans for drought response should be set up in advance; and prioritization plans for water use during drought are needed.

Currently, little drought response planning is undertaken in non-drought years, forcing institutions to improvise response plans as a drought event unfolds. Similarly, resources are not set aside in preparation for drought, but rather must be allocated ad hoc from other areas in the event of a drought. Laying out response and resource allocation plans in advance could decrease stress and improve response timing and efficacy during drought. The development of provincial water use prioritization plans can also help decision-makers manage water resources when faced with drought.

## Research Implications and Recommendations

Anticipated climate change impacts on the Prairies include more frequent and severe droughts (Sauchyn and Kulshreshtha, 2008). As such, through increased preparedness and research and development to improve information sources, institutions can reduce vulnerability and improve resilience to climate change (Wilhite, 1996; 2002). The proper education and timely dissemination of research results and data is crucial, as

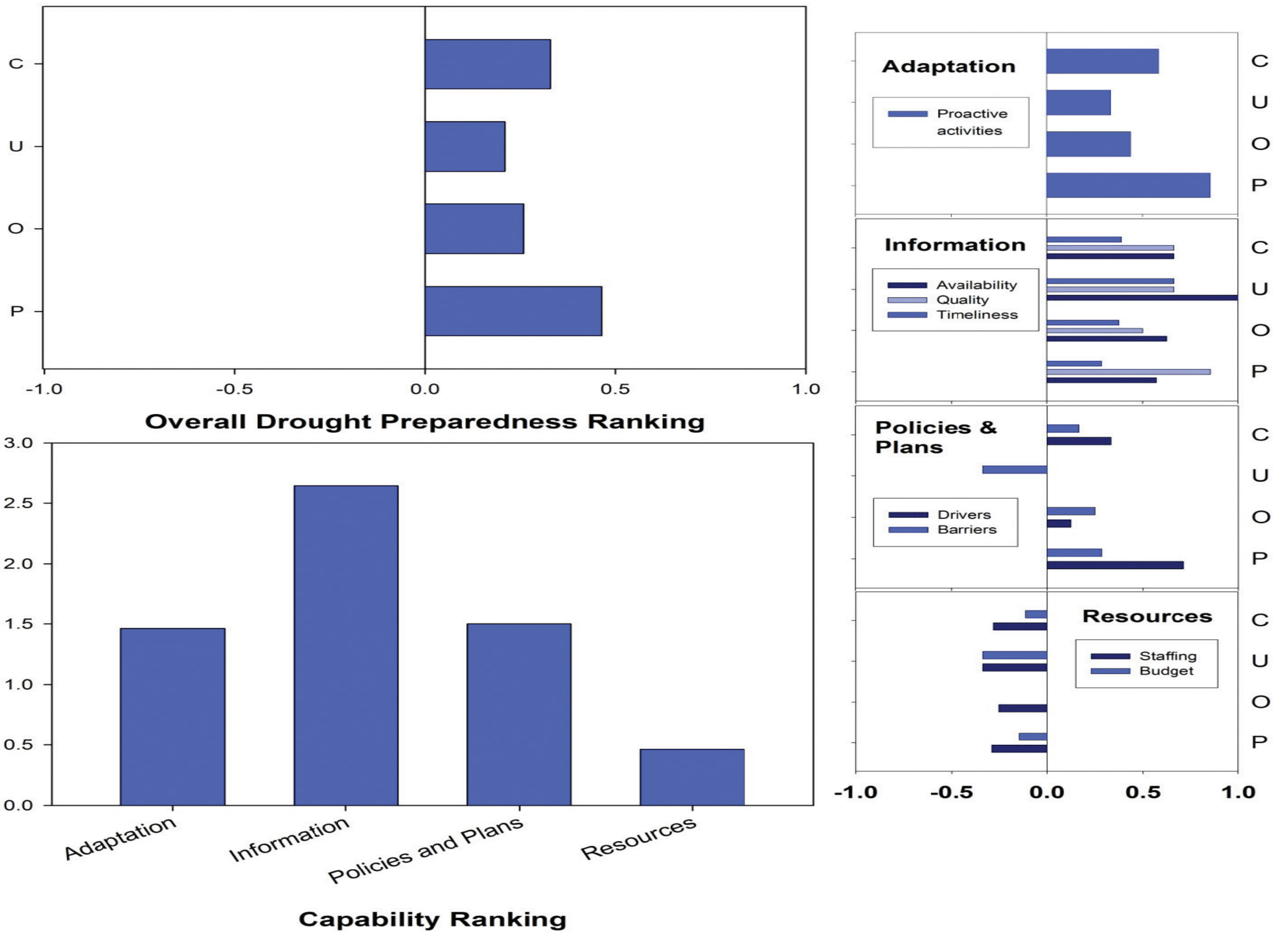


**Figure 3.** Overall drought preparedness (C=Combined, U=Unmarked, O=Observers, P=Participants).

information is only valuable if it is readily available and properly understood. This work encourages further efforts to address the research-to-operations knowledge gap.

Proactive risk management is important for crisis aversion. Shifting institutionalized drought response perspectives from crisis to risk management is a major contribution to climate change adaptation. This research helped identify ways in which institutions in Saskatchewan and Manitoba can become better prepared for drought. Strengths and weaknesses in drought preparedness were discovered and steps identified to address constraints. It is hoped that this research forms the basis for drought-preparedness institutionalization within government agencies across Canada.

To this end, the following recommendations were developed: first, we must continue education and the distribution of research results by expanding the DPP and DEWS exercise within Saskatchewan and in other jurisdictions. Second, the multidisciplinary expertise of the members of the DRI network should continue to be utilized to add value to DPP and general drought planning. Finally, water-use prioritization planning with multiple stakeholders should be discussed by government agencies.

*Data Legacy, Outreach, and Policy*

# DRI RESEARCH AND ITS CONTRIBUTION TO SUSTAINABLE DEVELOPMENT DURING TIMES OF DROUGHT

*Richard Lawford*

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## Introduction

The agricultural industry is major source of employment and economic activity on the Canadian Prairies, especially in the southern Prairies, where arable land exists and the majority of the population lives. In this area, climate extremes such as droughts reduce agricultural production and profitability and can have a devastating impact on the overall economy and personal well-being of the population. Canada and the Prairie Provinces in particular devote considerable resources and effort to developing and implementing policies to ensure the sustainability of the agricultural sector.

Although sustainable development and sustainable agriculture are relatively new concepts that emerged from the Bruntland Commission report (World Commission on Environment and Development, 1988), agriculture has been trying to achieve this objective for the past century. Canada's economic development and environmental policies are shaped by its industrial and societal needs, which in turn are the result of its historical development as influenced by climate, the resource base, economic conditions, and its cultural and political orientations. While some of these factors are relatively constant, others can change rapidly, resulting in a dynamic interplay indicating that the factors which need to be in balance for sustainability are rarely in equilibrium. Furthermore, new factors such as globalization, with its economic and environmental implications, climate change, migration and adaptation policies, and technological innovation are acting to disturb the present equilibrium.

Sustainability must be considered at several levels. Sustainability for an individual farm relates to the viability of the producer's farming operation from one year to the next. At the national scale, sustainability relates to the overall agricultural sector and involves factors such as meeting the food requirements of Canadians and support of Canada's export goals.

Droughts are an intense climate signal that can disturb sustainable agriculture on farms and at the regional level. In the 1930s, a multi-year drought occurred at the same time as a global economic recession. For many farmers, agriculture was not sustainable and they left their farms to find other employment, often in different regions of the country. At the provincial or regional level farming almost became unsustainable, as annual farm production in the Prairie Provinces decreased from $432.5 million in 1925-1928 to $134.8 million in 1931-1934 and $175.7 million in 1935-1939 (Ankli, 1977). According to Karla Zubrycki (personal communication), her study with the International Institute of Sustainable Development (IISD) has shown that the innovations of the Noble Blade for plowing, a new poison for grasshoppers, the widespread use of Fairway Crested Wheat Grass, and the expansion of the Prairie Farm Rehabilitation Administration's (now the Agri-Environment Services Branch) programmes for dug-outs and community pastures all helped stabilize Prairie agriculture following this very difficult period.

Generalizing from specific research results acquired through DRI, this article focuses on the implications of drought research for the agricultural sector. DRI was initiated to improve our understanding of drought and drought predictions in ways that would lead to more sustainable agriculture. Drought events on the Canadian Prairies can be categorized as meteorological, hydrological, agricultural, socio-economic, or some combination of these manifestations (Maybank et al., 1996). Although the discussions in this article recognize the nuances of different types of drought, the more general term "drought" is used because the 1999-2005 drought was so severe that it affected hydrological patterns, reduced agricultural outputs, and produced socio-economic impacts in most parts of the Prairies. This article summarizes some of the findings as they relate to sustainable agriculture on three time scales: multi-year to decadal, seasonal to annual, and daily to weekly.

## Support for Sustainable Agriculture

Support to the agricultural sector during drought situations comes from many sources, such as policy-enabled insurance programmes, development programmes aimed at improving on-farm water availability, subsidized pasture and forage programmes, among others. All of these programmes rely on information and projections to support the decision to provide financial aid. New discoveries regarding the relationships between droughts, their impacts, and farming practices and productivity can lead to new information and products for operational information services. These products are continuously being improved in terms of quality and scope to take advantage of new scientific understanding, new observational data, and improved analysis services. In general, the results of discovery science contribute to the improvement of the information available for operations on all time scales. They also provide knowledge and data products that can improve the operational products that are delivered to producers and agribusinesses. Through its Partners Advisory Committee (PAC), Drought Early Warning System (DEWS) exercises, and user workshops, the DRI project has provided and communicated a scientific basis for better monitoring and prediction services and better tools for decision-making in the agricultural community.

Alberta's annual production statistics provide evidence that the coefficient of variance of crop yields is decreasing due to technology and the adaptation of modern farming practices. Exceptions to this are severe drought years such as those that occurred in 2001 and 2002, when yields were well below average in spite of these technological advances. While drought generally does not damage infrastructure, it can lead to irreversible effects when farming operations are abandoned, livestock herds and land are sold, and families move to other areas. While stories from the 1930s about such irreversible impacts are common, they appear to have been less common during the 1999-2005 drought even though precipitation anomalies of similar or even greater severity persisted in some regions.

There are a number of risks associated with farming operations, including input costs, equipment acquisition and maintenance, safety and health, weather, and economic conditions for grain sales. Decisions that are taken based on these risks often have benefits or impacts on short-term, medium-term, and long-term time scales. DRI research included a range of discovery science, information and data product development, evaluation, and the scientific results needed to inform prediction services and management at these time scales.

### Multi-year to Decadal

Canada's focus on agriculture takes advantage of a natural resource base in Western Canada that includes fertile soils, generally adequate water, and relatively flat topography. Drought impact mitigation actions at multi-year to decadal time scales are primarily policy actions or projects that result in new infrastructure that will last for many decades. Canada has built and currently maintains considerable infrastructure to support the agricultural industry, including dams and reservoirs to support irrigation and on-farm water supplies, road and rail systems to support transportation, and services in towns that support farming communities. Southern Alberta has addressed drought risks by establishing a network of irrigation channels and water reservoirs to increase the chances that crops will have adequate water in dry years. This type of resilience does not exist in Saskatchewan, except around Lake Diefenbaker, and has only recently been established in areas of Manitoba along the Assiniboine River, where an upstream reservoir provides reliable flows for irrigation of high-value vegetable crops. When planning new infrastructure such as dams, reservoirs, and irrigation systems, climate change information and its implications for future drought patterns must be considered. In addition to direct support for infrastructure, one of the government's most effective contributions to drought planning is funding for drought research. This enables the provision of timely services for better decision-making at the policy level and training of producers and other agricultural workers to use sophisticated information services, including climate information.

Changes in climate are not without precedent. Sauchyn (this volume) used tree-ring analysis to document the range of long-term variability of temperature and precipitation over the Canadian Prairies to show this area's potential vulnerability to prolonged periods of dryness. Climate change concerns are superimposed on this natural variability. According to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, climate change has the potential to bring significant changes to agriculture on the Canadian Prairies. Some areas are projected to become drier and experience a higher frequency of dry conditions. The structure of precipitation patterns is expected to change as well, and some experts suggest that even in those areas where total annual precipitation may increase due to more intense storms, there could be longer periods without precipitation, leading to more frequent dry conditions. In addition, warmer temperatures are expected to lead to higher evapotranspiration rates in the summer months, thereby intensifying drying rates.

Part of the analysis required for long-term planning must focus on climate variability and the statistics of this variability. A recent report by Milly et al. (2007) observed that “stationary is dead” and indicated that a new perspective for planning water resources is needed. Climate change effects on agriculture must be evaluated in the context of other changes such as increasing the efficiency of agricultural practices, fluctuations in economic conditions, and structural changes in industry that will affect the way in which information is used and plans for the future are developed.

Droughts affect the availability of water for agriculture. In some cases the allocations for irrigation water and other industrial uses now comprise a large proportion of the average annual available flow. In some areas, during years with drought and low flows it is possible for the river flows to be less than the amount of water that has been allocated for irrigation. Interprovincial agreements have been in place for a number of years to ensure that each Prairie province receives its share of the water. These interprovincial agreements are based on naturalized flows or the water that would be flowing in the rivers if there were no water use withdrawals and reservoirs. As Figure 1 shows, the natural flows in some rivers are not well correlated with measured flows during low flow or drought periods. This result indicates that during times of drought the corrections can become larger than the monthly flows in some rivers, suggesting that the uncertainties could be as large as the flow itself.

Baseline climate data are important for producers. Before purchasing a farm in a new area, producers would be advised to understand the climate variability of the area. Assessments of farmland should consider average temperature and precipitation conditions as well as the year-to-year variability and the frequency of those events (e.g., droughts, pluvial) that could decrease production. This assessment of baseline climate can provide insights into the type of farming that will be most successful in a given area. Some of the information being incorporated into the DRI legacy database could be helpful to producers assessing the potential impacts of drought in their area.

The DRI project has elaborated the impacts of a multi-year precipitation deficiency under current climate conditions. By planning responses to these events and taking appropriate action in advance of their occurrence, it is possible to reduce their impacts. Given that climate change may result in more intense and longer periods of drought in the future, DRI’s findings related to impacts provide a basis for assessing risk and vulnerability and for recommending adaptive strategies.

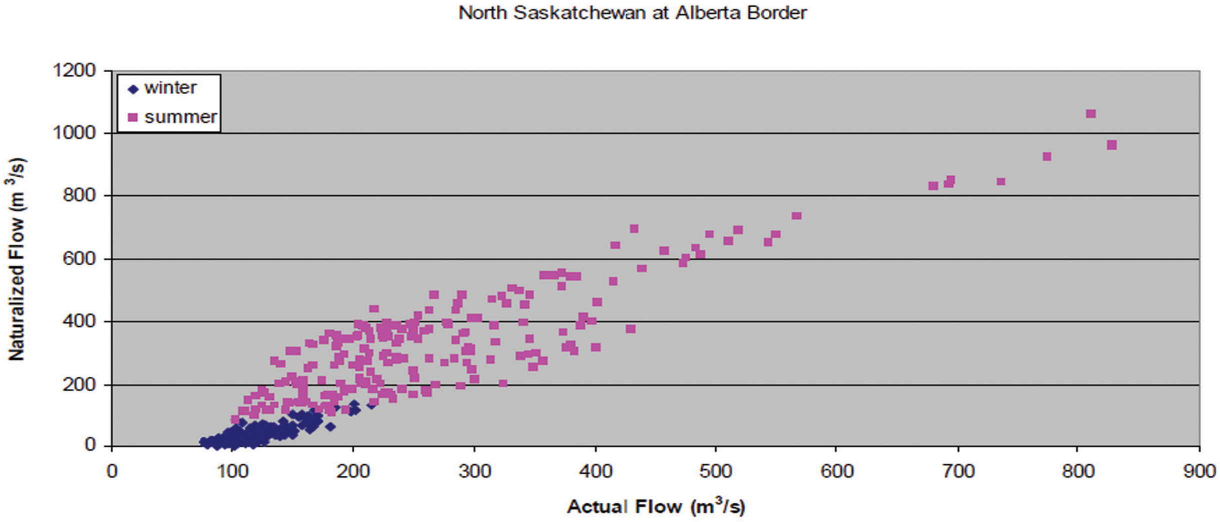

**Figure 1**. The variations of measured river flows and naturalized flows for the North Saskatchewan River at the Saskatchewan-Alberta border. The relationship between measured and naturalized flows is less accurate when low flows prevail.

**Seasonal to Annual**

Many decisions taken within the agricultural community would be improved by accurate seasonal forecasts because they involve planning decisions and commitments to purchases and actions with lead times of one or more seasons in advance of the growing season. When very dry conditions exist during the spring and the preceding winter, producers are faced with questions such as: "Should I plant a drought resistant crop?" or "Should I plant a crop at all?" Planting leads to questions about the levels of fertilization and pesticide application that would be appropriate under these dry conditions. Drought affects decisions at all levels of the industry because governments approve budgets and programmes, including agricultural programmes, with lead times of months and years, and agribusinesses need to estimate their sales potential and ensure they will have adequate inventories of seed, fertilizers, and pesticides up to two seasons ahead of the growing season. The lead times desired for forecast information by different user groups are summarized in Table 1. The precise dates of decisions may vary according to location, but these times are generally applicable within several weeks. Clearly, reliable seasonal and annual precipitation forecasts at lead times of up to twelve months are a missing link for making predictions that are useful to the agricultural community.

| | Lead Time in Months | | | | |
|---|---|---|---|---|---|
| | 12 months | 9 months | 6 months | 3 months | Start of the growing season |
| **Producers** | | | | | |
| - Crop Selection | | ▨ | ▨ | ▨ | ▨ |
| - Fertilizer/Pesticide Decisions | | | ▨ | ▨ | ▨ |
| - Cropping and Insurance Strategies | | ▨ | ▨ | ▨ | ▨ |
| **Government Crop Insurance** | ▨ | ▨ | ▨ | ▨ | ▨ |
| **Agri-Business** | ▨ | ▨ | ▨ | ▨ | ▨ |
| **Water Resources Management** | | ▨ | ▨ | ▨ | ▨ |

**Table 1**. A decision matrix of prediction information needs based on feedback obtained from producers and experts, including those attending DRI user workshops.

Crop insurance programmes are usually administered at the provincial level. These programmes have the effect of spreading the risk so that the benefits from good years can be transferred to the poorer dry years and the losses arising in a dry area from a dry year can be spread to other areas. In the past it was found that the estimates of soil moisture conditions used to determine insurance payouts for forage crops did not always match the field measurements. As a result of DRI research, better techniques have been developed to assess soil moisture conditions in pasture lands. These techniques and parameterizations are now being incorporated into Alberta government forage crop models.

With perfect forecasts it would be possible to reduce the uncertainty involved in decision-making and improve the overall quality of decisions. At present, Environment Canada's seasonal temperature forecasts show some skill but precipitation forecasts are less skillfull. Given the uncertainties in the current capability to produce reliable seasonal predictions of precipitation (not to mention uncertainties in the economy), it is clear that the strategies for responding to drought must incorporate a significant level of risk management. As a result, decisions are made on the basis of average climate statistics and, in some cases, the general seasonal climate trends arising from the presence or absence of El Niño conditions. DRI studies by Shabbar and others (this volume) suggest that there may be some potential to use Sea Surface Temperatures and planetary scale circulation patterns in an analogue prediction mode to anticipate the next season's most probable temperature and precipitation anomalies. Planning for agricultural activities would proceed differently if farmers could have predictions that gave them confidence that there would be a better than 50% chance that the next spring and summer would be drier than average.

Drought increases the demand for and use of irrigation water in those areas where irrigation is practiced. This increase in demand, however, usually comes at a time when droughts result in low flows and the water available for irrigation is at a minimum. Interestingly, in southern Alberta there appeared to be almost no increase in irrigation licences during the 1999-2005 drought. This suggests that it may be easier to increase the capacity to deal with drought conditions during a period when drought is not an issue.

Sustainability is facilitated by long-term planning and by timely decisions based on accurate seasonal predictions. DRI research has found that predicting the end of a drought is a major scientific challenge. It was a major problem during the spring of 2005 when the multi-year drought, which is the focus of this report, came to an abrupt end with a very wet period from April to June 2005 that was not anticipated by Environment Canada's seasonal precipitation forecasts. The experience of producers in this period suggests there is a need for analysis to determine the conditions under which a drought will end after it has lasted for a number of months or years.

Drought also has impacts on other sectors that contribute to the demand for reliable seasonal forecasts. The decreased number and area of wetlands during a drought impacts the ecology of the region, leading to reductions in the populations of ducks and other waterfowl. As wetlands dry out, the lengths of their perimeters are reduced and waterfowl no longer have as much habitat in which they can breed and raise their young. Hydropower production is dependent on the water levels that can in part be controlled by the rate of release of water from reservoirs throughout power production networks. Multi-year droughts impact hydroelectric production, particularly beyond the first year, after reservoirs have been drawn down. In forested areas, several successive years of drought can have severe impacts on forest fires and the dieback of aspen forests (Hogg, this volume). Furthermore, seasonal forecasts can be used to determine where firefighting equipment should be staged in anticipation of spring or summer fire seasons due to very dry forest conditions.

### Daily to Weekly

Information on these short time scales is important for informing producers of weather conditions so that they can determine the best actions on a given day or for the coming week. Many tactical farming decisions can be improved by considering a reliable five-day to two-week outlook. For example, producers rely on these forecasts to plan the timing of seeding, spraying, fertilizing, and harvesting. In Canada, this type of service is quite mature and reliable forecasts are available from the Meteorological Service of Canada. Although the daily to weekly time scale has not been a central focus for DRI, some insights were nevertheless developed about the individual storm events and the hydrological processes that occurred during the initiation, intensification, and cessation of drought.

Many producers also depend on information about current conditions when making decisions. Hanesiak et al. (this volume) have provided a number of insights and experimental products related to the monitoring of current conditions, including characterization of the drought in terms of soil moisture, vegetation cover, and precipitation. An evaluation of indices and datasets that could be used for drought monitoring services has shown that the indices can give different results depending on the input data used for the analysis. This result indicates that care must be exercised in the use of indices and input data, especially if the return frequencies of droughts are being considered.

Knowledge of current conditions can also help plan better on-farm practices. Bullock (this volume) has shown the relationship between water demand indices, including estimates of evapotranspiration, crop yield, and other crop properties. In general, these effects could be expected to be greater during dry conditions provided there was sufficient soil moisture and heat to support crop growth. This information could affect decisions related to the timing of harvest and the treatment of grain after harvest to improve its market quality.

Although some DRI products have considerable potential for monitoring drought (e.g., soil moisture), they are complex because they require the use of models or algorithms. There is a need for experts in operational agencies to learn how to deal with these complexities and to produce similar products on an ongoing basis. Groups such as AAFC's drought monitoring unit could strengthen their services by adopting some of DRI's products and capabilities. One opportunity area which is not fully exploited in Canada involves the use of satellite products. Although the Canada Centre for Remote Sensing (CCRS) works diligently at producing Normalized Difference Vegetation Index (NDVI) and other maps, other satellite products could be developed and operationalized for the benefit of Canadian agriculture. This could be achieved most effectively if operational drought centres were given the resources to exploit satellite data for the benefit of better drought monitoring, especially in areas where observational networks are sparse. DRI has been contributing to the Global Earth Observation System of Systems (GEOSS) in the area of drought monitoring and its data legacy project is seen as a way to use both distributed and centralized archiving capabilities to provide data-access services to users. DRI is actively involved in the Group on Earth Observations' efforts to make drought monitoring information available on a global basis to enable all nations to be aware of their vulnerabilities and to quantify the local risk of drought.

## Strategies to Enhance Sustainable Agriculture through Better Water Management in Dry Periods

Water is a central element in successful and sustainable agriculture. DRI research has produced a knowledge base and a number of tools to help with water management decisions. This information could serve as general background on how to respond to drought conditions and could be actively incorporated into decision processes.

### What Producers Can Do

During droughts, water conservation principles should be adopted both in tillage practices and direct water use. On the Canadian Prairies it is often possible to retain snow on a field during the winter and to take actions to encourage the snowmelt to infiltrate the soil during the spring. To some extent, residual stubble over winter will retain snow on the fields. Hydrological models being developed within DRI could be used to assess the efficiency of snow retention and its contributions to soil moisture through this practice. Other actions should include the selection of drought-tolerant crops and the reduced use of fertilizers and pesticides during dry conditions.

**What Governments Can Do**

Provincial governments provide financial assistance with the implementation of irrigation systems. In southern Alberta, where a network of channels exists to bring water close to farms and the value of the crops are high, there is an attractive cost-benefit ratio for irrigation systems. For flood irrigation, the channels must be vigilantly maintained to minimize leakage losses. Furthermore, new pivot irrigation technologies should be adapted as they develop to ensure that the most efficient means of delivering water from the nozzle to the crop canopy is being used. DRI research could be helpful in assessing requirements for irrigation water during drought. However, one aspect of irrigation that was not considered by DRI is the need to balance water availability, crop value, and energy use during droughts.

Development of improved aquifer management practices, including the joint planning for surface water and groundwater, could be helpful in ensuring that rural water supplies continue to be available under drought conditions. In appropriate areas this could include practices such as allocating surface water for water demands in periods where there is plenty of water and utilizing groundwater only in drought situations. Such strategies could also include encouraging producers to keep water on the landscape for as long as possible to maximize its contribution to groundwater recharge.

Some of the past farm assistance programmes during drought have focused on increasing on-farm water supplies. This is a traditional approach to agriculture in mixed-farming areas to support livestock and on-farm watering needs, particularly during droughts. It often includes the construction of new water storage facilities (e.g., dugouts). Given that many of the farms needing dugouts may have them by now, it may be appropriate to review this policy to assess the incremental benefits of adding more dugouts and to determine if other approaches to drought impact alleviation may be more effective.

## Summary

Drought is part of the natural climate cycle on the Canadian Prairies. During past Prairie drought events, the agricultural industry and the economy in general experienced difficulties although, in more recent years, producers appear to have avoided the impacts of drought more than they did in the 1930s. There is reason to believe, however, that the impacts of drought on farm productivity could be reduced even further with better seasonal forecasts, better monitoring, improved impact assessment models, and better planning. Support for mitigating the impacts of drought is needed at three time scales: multi-year to decadal, seasonal to interannual, and daily to weekly. DRI has provided a scientific basis for better predictions and improved information services, including monitoring information, for farmers who could benefit from decisions at all three time scales.

DRI has helped elaborate the impacts of a precipitation deficiency under current climate conditions. The precipitation deficiency of the 1999-2005 drought led to soil moisture deficiencies that affected plant growth and runoff. This cycle, which has been documented by Hanesiak (this volume), led to crop reductions and forest impacts (Hogg, this volume). Past knowledge of the ways in which precipitation deficits lead to drought impacts is very useful for identifying the vulnerable parts of ecosystems and could lead to actions to reduce those effects. This type of study would be best carried out with a well-planned data collection system that obtains observations of the environment as they occur rather than pulling together data from disparate sources after the event, as DRI has done to a large extent for its analysis of the 1999-2005 drought.

A number of factors affect society's adaptation to drought events. Short-term decisions would be aided by higher-resolution data products for monitoring drought. To a large extent, long-term decisions rely on risk reduction approaches. Since climate change will likely introduce more uncertainties regarding the availability of water resources in a specific location, it should be addressed by building more resilience into systems based on an assumed future with more frequent and intense drought events. The response to drought on the medium time scale could most effectively come through the development of better information support for decision-making through improved seasonal forecasts. DRI made some progress on this issue, particularly in developing the capability to interpret precipitation anomalies in terms of their impacts on local water availability. Currently, models are better at predicting temperature anomalies than precipitation anomalies. Medium-term resilience could also be improved with better advice from modelling tools. In the longer term, energy considerations will be a central issue, both in terms of costs and the environmental impacts associated with different response options. While DRI has made substantial progress in addressing drought monitoring, impact assessment, and hydrological prediction issues, many research questions related to drought response and prediction on the seasonal to decadal time scales remain.

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*Conclusion*

# SUMMARY OF SCIENCE, IMPACTS, AND LESSONS

*Ronald Stewart, Richard Lawford, and John Pomeroy*

This publication provided highlights from the majority of studies undertaken by the Drought Research Initiative between 2005 and 2010. The range of articles presented here demonstrates the breadth and richness of the understanding that emerged from this research. These articles have described DRI's major achievements in terms of new knowledge gained, new models, new products, and new applications. For more comprehensive treatment of individual topics, readers are encouraged to explore the published literature produced by individual investigators as well as a special issue of *Atmosphere-Ocean* that is currently in preparation. The DRI website (www.drinetwork.ca) also continues to provide access to an extensive archive of data and information on DRI workshops, annual reports, and publications.

To the best of our knowledge, DRI is the first study to bring together such a wide range of interdisciplinary expertise and experience to look at a historic drought event. This approach to drought research, which combined the analysis of historic data with process studies, model development, and simulations, has proven to be very useful. The increased process understanding that has come about through the studies reported here provides a basis for assessments of the limitations of models and helps clarify many of the special issues that multi-year droughts pose for prediction. For example, the large-scale atmospheric processes that account for the establishment of periods of low precipitation are more complex than originally thought. Shorter-term droughts such as the one that occurred in 1988 typically were dominated by a characteristic circulation regime, while this multi-year drought persisted through several large-scale circulation regimes. As a result, some drought years had average or above-average cloudiness and cooler-than-average summer temperatures. It appears that after the circulation regime had set up the drought, it was followed by other circulation regimes that were not able to break the drought, possibly because of the importance of land-atmosphere interactions or smaller regional-scale circulations.

In terms of smaller-scale processes, the relative importance of some processes increased during the drought. In the atmosphere, higher cloud bases led to virga (precipitation that falls from the base of the cloud but evaporates before it reaches the surface). Virga processes are either not well handled or not included in the precipitation schemes used in prediction models. Another related study indicated that droughts are more strongly associated with suppressed precipitation than lowered atmospheric moisture contents.

Hydrologic studies reported here emphasized the role of groundwater in responding to drought conditions. As the drought progressed, groundwater levels decreased. In some types of soils, groundwater-atmosphere interactions became very important as the surface layer dried out and the atmosphere attempted to draw moisture from groundwater reserves. As part of this drying process wetlands, soil moisture, and surface water reserves dried out. Substantial progress has been made within DRI in modelling these processes and incorporating their parameterizations into more complex prediction models.

DRI also examined the heterogeneity of drought patterns. Within drought areas, convective storms led to local precipitation maximum embedded in areas of precipitation minimum. During the 1999-2005 drought, several heavy rain events associated with large summer storms gave above-average rainfalls within much larger areas characterized by very dry conditions. Furthermore, the multi-year drought came to an end in rather dramatic fashion as heavy rains flooded farmland in Manitoba during the spring of 2005, suggesting that the interactions between extremely dry conditions and heavy rain events need to be better understood.

The impacts of the drought and the land-atmosphere interactions were also described in this report. DRI research showed the role of drought in constraining crop growth both in terms of the quantity and protein levels of wheat. Crop status appears to be correlated with water demand drought indices, including evapotranspiration. Evapotranspiration from crops plays an important role in moistening the atmosphere and helps to explain the connections between land cover and atmospheric moisture content. These connections extend to surface hydrology during drought, as wetlands dry up and reduce the availability of water for plants and the atmosphere. The groundwater version of the Canadian Land Surface Scheme (gCLASS) model, developed and calibrated for the Assiniboine Delta Aquifer, and the Cold Regions Hydrological Model (CRHM) provide frameworks for assessing the interactions between atmospheric, hydrologic, and biospheric systems. The analyses reported here demonstrate that meteorological, agricultural, and hydrological data are all useful in characterizing and monitoring drought. However, DRI studies also showed that the portrayal of drought intensity and impacts is sensitive to the index chosen and datasets used to calculate these indices (such as gridded precipitation datasets from different sources). It is important to understand these relationships when developing a drought monitoring system.

DRI also supported outreach activities. The DRI Data Legacy information system was developed to allow researchers, resource managers, producers, and other users to access the archive of data, workshop presentations, and reports that DRI has accumulated. In addition, the implications of DRI research for sustainable development have been assessed and Agriculture and Agri-Food Canada (AAFC) continues to develop more complex multi-year drought simulations than those used in the drought preparedness exercises described here. For DRI, these simulations facilitated interactions with users while testing drought monitoring products and promoting drought preparedness. The results of DRI will also live on in international programmes such as the Global Earth Observation System of Systems (GEOSS) and the Global Energy and Water Cycle Experiment (GEWEX), to which DRI scientists contribute their expertise and findings.

DRI leaves behind a substantial footprint. It has produced research results that have benefited government policy-makers and producers. Much of the research presented here has been aided by graduate students and research associates who are now equipped with the skills and knowledge needed to develop successful careers in the climate and hydrological sciences. Collectively, DRI has developed a network of experts and its linkages with users continue to grow. Readers are encouraged to engage with the authors who contributed to this report and to continue to participate in discussions about drought adaptation. It is important that we continue to incorporate these research results into broader discussions of Canadian society's adaptation to climate variability and change.

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# GLOSSARY

| | |
|---|---|
| **AAFC** | Agriculture and Agri-Food Canada |
| **ABA** | Abscisic Acid |
| **ADA** | Assiniboine Delta Aquifer |
| **AECL** | Atomic Energy of Canada Limited |
| **AESB** | Agri-Environment Services Branch |
| **AGAME** | Alberta GPS Atmospheric Moisture Evaluation |
| **AGU** | American Geophysical Union |
| **AMO** | Atlantic Multi-Decadal Oscillation |
| **AO** | Arctic Oscillation |
| **ARPEGE** | Action de recherche petite échelle grande échelle |
| **AVHRR** | Advanced Very High Resolution Radiometer |
| **BERMS** | Boreal Ecosystem Research and Monitoring Sites |
| **BOREAS** | Boreal Ecosystem-Atmosphere Study |
| **CAR** | Census Agricultural Region |
| **CCCMA** | Canadian Centre for Climate Modelling and Analysis |
| **CCP** | Canadian Carbon Program |
| **CCRS** | Canada Centre for Remote Sensing |
| **CFCAS** | Canadian Foundation for Climate and Atmospheric Sciences |
| **CG** | Cloud-to-Ground (Lightning) |
| **CIPHA** | Climate Impacts on Productivity and Health of Aspen |
| **CLASS** | Canadian Land Surface Scheme |
| **CLDN** | Canadian Lightning Detection Network |
| **CLIVAR** | Climate Variability and Predictability |
| **CMC** | Canadian Meteorological Centre |
| **CMI** | Climate Moisture Index |
| **CPC** | NCEP Climate Prediction Centre |
| **CPU** | Core Processing Units |
| **CRCM** | Canadian Regional Climate Model |
| **CRHM** | Cold Region Hydrological Model |
| **CWN** | Canadian Water Network |
| **DAI** | Data Access and Integration |
| **DEWS** | Drought Early Warning System |
| **DPA** | Drought Preparedness Assessment |
| **DPP** | Drought Preparedness Partnership |
| **DRI** | Drought Research Initiative |
| **EC** | Environment Canada |
| **ECMWF** | European Centre for Medium-Range Weather Forecasting |
| **ENSO** | El Niño-Southern Oscillation Cycle |
| **ERA-40** | ECMWF 40-year Reanalysis |
| **ET** | Evapotranspiration |
| **ETDI** | Evapotranspiration Deficit Index |
| **FLOW** | Forum for Leadership on Water |
| **gCLASS** | Groundwater version of the Canadian Land Surface Scheme |
| **GCM** | Global Climate Models |
| **GDP** | Gross Domestic Product |
| **GEM** | Global Environmental Multiscale Model |
| **GEO** | Group on Earth Observations |
| **GEOSS** | Global Earth Observation System of Systems |
| **GEWEX** | Global Energy and Water Cycle Experiment |
| **GLERL** | Great Lakes Environmental Research Lab |
| **GPS** | Global Positioning System |
| **GRACE** | Gravity Recovery and Climate Experiment |
| **IISD** | International Institute of Sustainable Development |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **ISCCP** | International Satellite Cloud Climatology Project |
| **ISO** | International Standards Organization |
| **IUGLS** | International Upper Great Lakes Study |
| **MAGS** | Mackenzie GEWEX Study |
| **MC** | Moisture Convergence |
| **MCA** | Maximum Covariance Analysis |
| **MEC** | Modélisation Environnementale Communautaire |
| **MESH** | Surface hydrology component of MEC |
| **MODIS** | Moderate Resolution Imaging Spectroradiometer |
| **MSC** | Meteorological Service of Canada |
| **NARR** | North American Regional Reanalysis |
| **NAO** | North Atlantic Oscillation |
| **NASA** | National Aeronautics and Space Administration |
| **NBS** | Net Basin Supply |
| **NCEP** | National Centers for Environmental Prediction |
| **NCEP-R2** | National Centers for Environmental Prediction - Reanalysis 2 |
| **NDVI** | Normalized Difference Vegetation Index |
| **NTS** | Net Total Supply |
| **PAC** | Partners Advisory Committee |
| **PAMII** | Second-generation Agrometeorological Model |
| **PARC** | Prairie Adaptation Research Collaborative |
| **PAW** | Plant Available Water |
| **PDO** | Pacific Decadal Oscillation |
| **PDSI** | Palmer Drought Severity Index |
| **PFRA** | Prairie Farm Rehabilitation Administration |
| **PNA** | Pacific North American Oscillation |
| **PUB** | Predictions in Ungauged Basins |
| **RCM** | Regional Climate Model |
| **RH** | Relative Humidity |
| **RMSE** | Root Mean Square Error |
| **SABAE-HW** | Soil Atmosphere Boundary, Accurate Evaluations of Heat and Water |
| **SaskEMO** | Saskatchewan Emergency Management Organization |
| **SGI** | Saskatchewan Government Insurance |
| **SHAW** | Simultaneous Heat and Water |
| **SM** | Soil Moisture |
| **SMAPI** | Soil Moisture Anomaly Percentage Index |
| **SPI** | Standardized Precipitation Index |
| **SRB** | Surface Radiation Budget |
| **SRC** | Saskatchewan Research Council |
| **SST** | Sea Surface Temperature |
| **SVAT** | Surface Vegetation Atmosphere Transfer |
| **SWA** | Saskatchewan Watershed Authority |
| **TAW** | Total Available Water |
| **TOA** | Top of the Atmosphere |
| **TSD** | Total Storage Deficit |
| **UNSTABLE** | The Understanding Severe Thunderstorms and Alberta Boundary Layers Experiment |
| **VIC** | Variable Infiltration Capacity model |
| **WCRP** | World Climate Research Programme |
| **WS** | Water Stress |
| **WU** | Water Use |

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