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DRI
Drought Research Initiative
Initiative de recherche sur la sécheresse

CMOS Bulletin SCMO
"at the service of its members / au service de ses membres"

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This issue : Large-area, prolonged droughts are among Canada's costliest natural disasters having major impacts on a wide range of sectors including agriculture, forestry, industry, municipalities, recreation, health and society, and aquatic ecosystems. Although most regions of Canada experience drought, the Canadian Prairies are most susceptible with at least 40 droughts being documented during the past two centuries. However, rarely has drought been as serious or extensive as the recent 1999-2005 episode that produced the worst drought for at least a hundred years in many parts of the Canadian Prairies. To aid in addressing such extreme drought events, the Drought Research Initiative (DRI) research network has been established. The focus of DRI is to better understand the factors that led to, sustained and ended this recent drought with a view to understanding its structure and to contributing to the better anticipation of such events. To accomplish this objective, the drought is being considered from several perspectives involving atmospheric, surface (including vegetation) and sub-surface processes. Furthermore the DRI research community is working closely with many partners affected by the drought so that they can better cope with such events in the future.

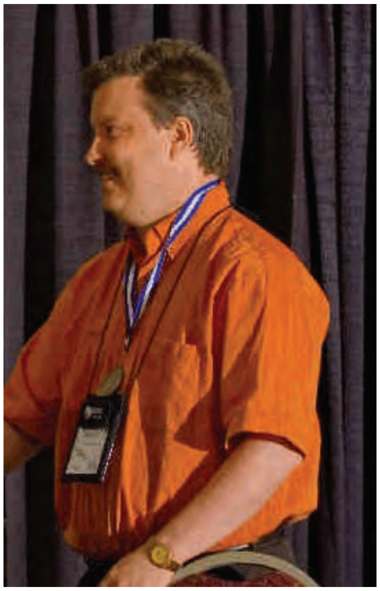
Three articles in this issue address Canadian droughts with a focus on the ongoing DRI Network. An overview of droughts in Canada is initially presented on **page 79** with an emphasis on those occurring over the Canadian Prairies. This is followed by a description on **page 87** of the many facets of DRI. The issue concludes with an assessment of the user community's expectation of DRI including their identified needs on **page 97**.

Cover page: The cover page photo was taken near Consul, Saskatchewan in April 2002. Photo courtesy of Ted Banks, Agriculture and Agri-Food Canada.

Note du Rédacteur: Vous trouverez la description française de ce numéro thématique ainsi que de la page couverture à la **page 102**.

....from the Presidents' Desks

Friends and colleagues:



Paul Myers
Outgoing President of CMOS
Président sortant de la SCMO

Now that June has arrived, I am amazed at how fast the past year has gone by and then my time as CMOS President has come to an end. In some ways this is a relief in that I can go back to focussing on some interesting research questions that I'd like to look at. Yet, I am also disappointed that this year is over so fast because of how much I have learned about aspects of science, especially on the governmental and management side, and how much more I'd like to learn and be involved in different things that I only got a chance to touch on during the past year.

And I do think this last issue is important. As scientists/forecasters, most of us want to spend their time focussing on what we all love, our favourite aspects of meteorology and oceanography. Yet, addressing the issues that impact our field, as well as communicating our science to the general public are issues of great importance. And it is something that I suspect almost all of us can do better - I sure learnt that during this year as CMOS President. And one way for this to occur is to become more involved with CMOS, as the society continues to represent and promote meteorology and oceanography in Canada. And thus, echoing all previous CMOS presidents in their final words, I highly recommend members to get involved as CMOS volunteers in your Centres, and on national committees or Council.

Finally, I would like to thank those in the national office in Ottawa, especially our executive director Ian Rutherford, without whom I would not have survived this year, and without which the society would not function. And so to conclude I wish the best for our new incoming president Andy Bush as I prepare to pass off the position to him.

Paul Myers

Outgoing President / Président sortant
Canadian Meteorological and Oceanographic Society
Société canadienne de météorologie et d'océanographie

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Inside / En Bref

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CMOS exists for the advancement of meteorology and oceanography in Canada.

Le but de la SCMO est de stimuler l'intérêt pour la météorologie et l'océanographie au Canada.

Andy Bush
Incoming President of CMOS
Nouveau président de la SCMO

Being literally next door to Paul Myers, I can attest to the amount of effort he has put in as President of CMOS. I think we owe Paul a huge collective thanks for his efforts over the past year and, Paul, have one fantastic and well-earned sabbatical! I would also like to thank and pay my respects to Ian Rutherford, for steering things in the right way, at the right time.

The next few years will be challenging indeed. With the potential end of funding through the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) it is not clear what avenue researchers in Atmospheric, Oceanic, or Cryospheric Sciences might pursue given NSERC's woeful history for Environmental Sciences reallocations. One hopeful pursuit will be continuing our link with the Canadian Geophysical Union (CGU) and I am optimistic that we can form a unified front for geophysics, atmospheric physics, oceanography and cryospheric dynamics. Our joint meeting last year in St. John's, NF, was in my opinion an enormous success and I wish to pursue this link with the current president of CGU, John Pomeroy.

The collective public appears to be concerned about climate change and impacts on Canada. We are the natural organization to speak to this issue, to educate the public, to educate the political parties, and to educate industry. The latter two are difficult, of course. With Arctic climate becoming such an ironically hot topic we need to be at the forefront of educating those people who will be relevant players in the future of our North. This is not an easy task but I'll try, in the coming year, to do my best.

Andy Bush

Incoming President / Nouveau président
Canadian Meteorological and Oceanographic Society
Société canadienne de météorologie et d'océanographie

Highlights of Recent CMOS Meetings

March Council Meeting

- Updating status of Congresses: Kelowna, 2008, Halifax, 2009 and Ottawa, 2010;
- Discussing the relevent agreements needed between CMOS and CGU for the 2010 congress to be joint between the two societies;
- Updates on new membership applications and society membership numbers;
- Overview of the status of the CMOS Tour Speaker this year - what had occurred and which talks were still to be given;
- Council approval of nominees for awards from the Prizes and Awards Committee;
- Council approval of Fellow candidates from the Fellows Committee;
- Discussion of issues related to awards, membership and getting sufficient nominations for some awards (i.e. not all CMOS awards will be awarded this year because of a lack of nominations, even with extensions of the deadlines);
- Appointment of CMOS Audit Committee;
- Discussion of the possibility of having flight service specialists become part of CMOS, with CMOS governing their accreditation process;
- Approval of an update policy on travel expenses;
- Presentation of a discussion paper on congress finances, with a decision to use the Halifax congress (with the agreement of the Halifax LAC) as a test bed for dealing with more of the finances at a national level;
- Presentation of a discussion paper related to CMOS' financial investments and what rate of return the society should look to get, considering the needs to preserve the capital versus growth;
- Discussion of the society draft budget for 2008-09 prior to the AGM at Kelowna;

Paul Myers,
CMOS President
Président de la SCMO

URGENT - URGENT - URGENT - URGENT

Next Issue *CMOS Bulletin SCMO*

Next issue of the *CMOS Bulletin SCMO* will be published in **August 2008.** Please send your articles, notes, workshop reports or news items before **July 4, 2008** to the address given on page ii. We have an URGENT need for your written contributions.

Droughts in Canada: An Overview

by Barrie Bonsal[1]

Résumé: Les sécheresses menacent sérieusement la société et l'environnement puisqu'en grande partie les activités humaines et la santé des écosystèmes sont dépendantes de l'apport suffisant en eau. Les sécheresses prolongées sur grande surface sont parmi les catastrophes naturelles les plus coûteuses au Canada. Elles ont des répercussions profondes sur tout un éventail de secteurs, notamment sur l'agriculture, les forêts, l'industrie, les municipalités, les loisirs, la santé, la société et les écosystèmes aquatiques. Bien que la plupart des régions du Canada doivent faire face à la sécheresse, ce sont les régions du sud des Prairies canadiennes qui sont les plus vulnérables en raison de leurs précipitations spatio-temporelles éminemment variables. Cet article donne une vue d'ensemble des sécheresses au Canada et met l'accent sur les Prairies canadiennes. Tout d'abord, avec l'appui des données des instruments et des registres anciens, on fait une revue des tendances du passé et de la variabilité de la présence des sécheresses à travers le pays. Par la suite, on décrit les connaissances existantes en rapport avec les causes atmosphériques à grande échelle reliées à la sécheresse canadienne. On y discute aussi des sécheresses futures. On y présente les techniques de contrôles actuelles, les capacités de la modélisation et de la prévision, et les stratégies d'adaptation des sécheresses canadiennes. En conclusion, l'article met l'accent sur l'identification des lacunes majeures de la recherche et des besoins de programmes concernant les sécheresses sur l'Amérique du Nord qui pourraient nous aider à comprendre et prévoir leur présence, à contrôler et modéliser leur état, et à s'adapter à leurs effets négatifs.

Introduction

Droughts are one of the most dramatic manifestations of variations in the water cycle. Prolonged, large-area droughts are among Canada's costliest natural disasters having major impacts on a wide range of sectors including agriculture, forestry, industry, municipalities, recreation, human health and society, and aquatic ecosystems. They frequently stress water availability by depleting soil moisture, reducing stream flows, lowering lake and reservoir levels, and diminishing groundwater supplies. This ultimately affects several economic activities including, for example, decreased agricultural production, less hydro-electric power generation and increased freshwater transportation costs. Droughts also create major environmental hazards such as reduced water quality, wetland loss, soil erosion and degradation and ecological habitat destruction. Moreover, in response to the economic and environmental significance of droughts, scientific concern has been expressed regarding climate-change impacts on future drought frequency, duration and severity over various regions of the globe including Canada.

Droughts are complex phenomena with no standard definition. Simply stated, drought is a prolonged period of abnormally dry weather that depletes water resources for human and environmental needs (MSC Drought Study Group, 1986). However, each drought is different depending on factors such as area affected, duration, intensity, antecedent conditions and the region's capability to adapt to water shortages. Droughts also differ from other disasters (e.g., floods) since they have long durations, and lack easily identified onsets and terminations. Furthermore, their recurrence in drought-prone areas is practically certain since drought is characteristic of dry environments (Maybank et al., 1995). Droughts occur on a variety of temporal and spatial scales with their impacts being dependent on the timing and sequencing of dry periods. For example, a shortage of water and soil moisture at a critical time for crop growth may initiate agricultural drought, but hydropower generation would not be affected if reservoirs have adequate supplies. Climate anomalies that last from a month to years are the root of most droughts, however, human impacts on resources and climate and the changing demand for water are also major contributing factors (McKay et al., 1989).

Although most regions of Canada have experienced drought, southern regions of the Canadian Prairies and interior British Columbia are more susceptible mainly due to their high variability of precipitation in time and space. During the past two centuries, at least 40 droughts have occurred in western Canada with multi-year episodes being observed in the 1890s, 1910s, 1930s, 1960s, and 1980s (Phillips, 1990; Chipanshi et al., 2006). Droughts in southern Ontario/Quebec are usually shorter, smaller in area, less frequent and less intense. Nonetheless, there have been some major drought occurrences during the 20th century. Droughts in the Atlantic Provinces occur even less frequently. This reduced occurrence results in lower adaptive capacity, thus making the region more susceptible to drought impacts. Droughts are less of a concern for northern Canada mainly due to lower population densities. However, increased frequencies of forest fires during drought years can have serious economic impacts.

[1] Environment Canada, Saskatoon, Saskatchewan, Canada

Drought has, and continues to be a major concern in Canada but rarely has it been as serious or extensive as the recent 1999-2004 episode. This event produced the worst drought for at least a hundred years in parts of Canada and in particular, the Canadian Prairies. Well below normal precipitation was reported in areas of Alberta and Saskatchewan for more than four consecutive years extending from autumn 1999 to spring 2004. 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 (Phillips, 2002). This recent drought was also unusual in terms of its vast spatial extent. In particular, the years 2001 and 2002 may have brought the first coast-to-coast droughts on record, and were rare as they struck areas that are less accustomed to dealing with droughts including parts of Atlantic Canada and the northern agricultural prairies.

Unlike previous droughts that impacted few sectors, the 1999-2005 event affected many sectors including agriculture, recreation, tourism, health, hydro-electricity and forestry. Long-lasting impacts included soil degradation by wind erosion and deterioration of grasslands that could take decades and longer to recover. Canada's Gross Domestic Product fell $5.8 billion for 2001 and 2002, with the larger loss in 2002 at more than $3.6 billion. Drought also contributed to a negative net farm income in several provinces for the first time in 25 years (Wheaton et al., 2005). Previously reliable water supplies such as streams, wetlands, reservoirs, and groundwater were placed under stress and often failed. For example, the number of natural Prairie ponds in May 2002 was the lowest on record while in 2001, Great Lakes-St. Lawrence water levels plunged to their lowest point in more than 30 years thereby significantly increasing marine transportation costs. In British Columbia and Manitoba, hydro-electric generation was curtailed, necessitating additional purchases of power from neighbouring jurisdictions. In 2002, the incidence of forest fires in Alberta increased to five times the ten-year average while in summer 2003, populated regions of interior British Columbia were stricken by drought-enhanced fires.

Past Trends and Variability

Past drought research in Canada has been fragmented and often based on severe drought occurrence (e.g., the Drought Research Initiative described later in this issue). Nonetheless, there has been some effort to define large-scale trends and variability in various drought-related indices during the period of instrumental record. A problematic issue for most of these trend analyses is that they have been carried out independently with limited attempts in deriving comprehensive results for the entire country. They also often differ in terms of starting dates for trend calculation, and with respect to initial conditions for determining drought indices. Furthermore, the limitation of the instrumental record to approximately the last 100 years, combined with sparse high-resolution paleo-climatic information in areas that are most prone to drought, makes inference of long-term trends in Canadian droughts very difficult. Examples of trends and variability in various drought-related parameters are provided below.

High surface temperatures can intensify drought conditions through enhanced evapotranspiration in summer, and increased sublimation and melting of the snowpack during winter. Several studies have identified significant trends in temperature and various temperature-related indices over Canada during the 20th century. Mean annual air temperature has increased by an average of 0.9°C over southern Canada for the period 1900-98. The greatest warming was observed in the west and the largest rates occurred during winter and spring (Zhang et al., 2000). Much of the country has also experienced significant trends toward longer frost-free periods (Bonsal et al., 2001b) which could impact drought occurrence since these trends translate into a longer ice-free season for lakes and rivers thus increasing the potential for open-water evaporation. From 1900-98, annual precipitation has significantly increased over most of southern Canada with the exception of southern Alberta and Saskatchewan. This pattern is generally evident during all seasons (Zhang et al., 2000). The period 1915-97 was associated with substantial inter-decadal variability in North American snow cover including lowest anomalies in the 1920s and 1930s and highest during the late 1970s and early 1980s. Coincident with the large increases in spring temperature, the 1980s/90s were characterized by rapid reductions in snow cover during the second half of the snow season and especially during April (Brown, 2000).

Examples of 20th century Palmer Drought Severity Index (PDSI) time series for various regions of the country are provided in Figure 1 (Skinner, 2002). The series show considerable decadal-scale variability with no long-term trends discernible in any portion of the country. Most southern regions of Canada, however, were associated with anomalously negative PDSI values (i.e., drought conditions) during the late 1990s to early 2000s. In a study using the Standardized Precipitation Index (SPI) and PDSI as drought indicators, Bonsal and Regier (2007) showed that the worst and most prolonged Canadian Prairie-wide droughts during the period 1915 to 2002 occurred in the early part of the 20th century (1920s and 1930s). Sauchyn and Skinner (2001) reconstructed July PDSI for the southwestern Canadian Plains using tree ring chronologies dating back to 1597. Results showed that the 20th century lacked the prolonged droughts of the 18th and 19th centuries when the PDSI was consistently below zero for decades at a time. Clusters of drought years in the series suggested the existence of a 20 to 25 year periodicity over this region.

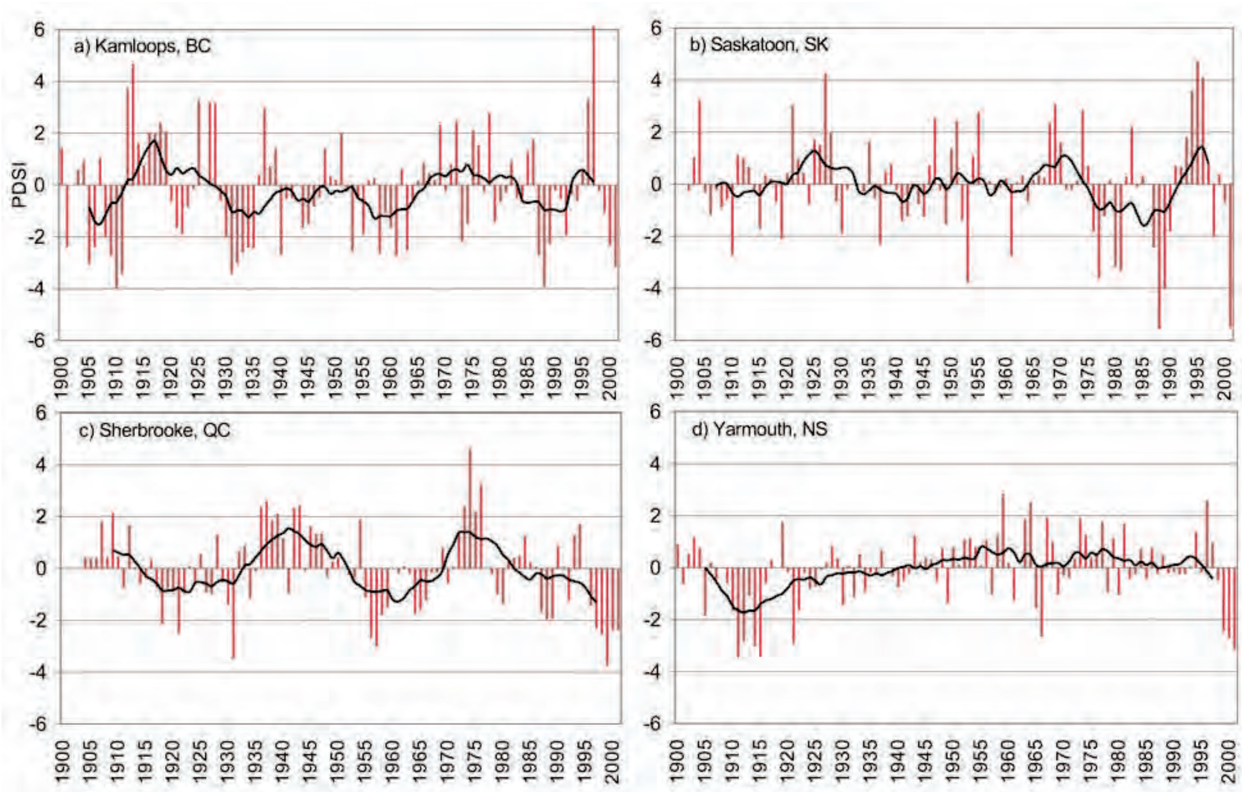

Figure 1: Annual PDSI values for a) Kamloops, BC, b) Saskatoon, SK, c) Sherbrooke, QC, and d) Yarmouth, NS. Solid lines represent 10-year running means. (Source: Climate Research Branch, Meteorological Service of Canada, Environment Canada, Downsview, ON.)

There have been some analyses of trends and variability in various water-related drought indicators over Canada, but these records tend to be much shorter. Over the last 30 to 50 years, mean stream flow has decreased in many parts of Canada with significant reductions in the south (Zhang et al., 2001). Great Lakes' water levels have shown considerable decadal-scale variability during the 20th century with no evidence of any long-term trend. Lower levels coincided with the droughts of the 1930s, early 1960s, and the most recent 1999-2001 dry period. Over the Prairies, the numbers and water levels of wetlands have shown no clear trend over the last 40 to 50 years (Conly and van der Kamp, 2001).

Large-Scale Causes

Although considerable research has been carried out on the subject of droughts, there is still no comprehensive theory that explains the physical mechanisms of their formation, maintenance, and termination. Droughts are caused by disruptions to an expected precipitation pattern and can be intensified by anomalously high temperatures. The major factor in the onset and perpetuation of drought involves anomalous circulation patterns in the upper atmosphere. Few studies have examined atmospheric causes of Canadian droughts with the majority focusing on western regions of the country. Over the agricultural region of the Canadian Prairies, growing season (May to August) extended dry periods were associated with a persistent upper-atmospheric circulation pattern that includes a large-amplitude ridge centred over the area. The ridging creates 'blocking conditions' that displace cyclonic tracks away from the area (e.g., Chakravarti, 1976). Drought conditions can also be initiated and/or accentuated during the cold season when a lack of precipitation results in lower than normal spring runoff and thus reduced stream flow and reservoir and soil moisture replenishment. Cold-season precipitation deficiencies are also influenced by persistent mid-tropospheric circulation patterns that involve anomalous ridging over the affected area (e.g., Shabbar et al., 1997).

Reasons for the persistence of anomalous circulation patterns that lead to drought are not entirely understood but are likely related to surface boundary conditions such as snow and ice cover, vegetation, soil moisture, and sea-surface temperatures (SSTs) that are known to force the climate system through variations in their optical and thermal properties (e.g. Maybank et al., 1995). The forcing factors directly influence local to regional atmospheric flow which in turn can affect large-scale circulation over other areas of the globe (known as teleconnections). Several studies have found relationships between various teleconnection indices and climate anomalies over North America. For Canada, significant relationships between El Niño/Southern Oscillation (ENSO) and winter/spring temperature and precipitation have been determined (Shabbar and Khandekar, 1996, Shabbar et al., 1997). Linkages between Canadian climate and teleconnections such as the Pacific Decadal Oscillation (PDO) and the North

Atlantic Oscillation (NAO) are also evident, but mainly during the winter season (e.g., Bonsal et al., 2001a). Teleconnections during summer are generally least robust as compared to winter. However, some association between North Pacific SST anomalies and atmospheric ridging leading to growing season extended dry spells over the Prairies has been identified (Bonsal et al., 1993). In addition, a study by Shabbar and Skinner (2004) indicated that ENSO, the PDO, and their interrelationship play a significant role in summer moisture availability in Canada. In particular, it was determined that El Niño events are associated with a summer moisture deficit in the western two-thirds of Canada while La Niñas produced an abundance of summer moisture in extreme western Canada. The considerable lag between summer moisture and large-scale SSTs provides a basis for developing long-range forecasting of drought conditions in Canada. Note that analyses of the large-scale atmospheric circulation patterns and teleconnections associated with the Canadian droughts during 2001 and 2002 revealed that the circulation was markedly different from that associated with previous severe droughts over western Canada. Moreover, the evolution and persistence of these droughts had no clear relationships with teleconnection patterns that have been shown to influence past climate extremes over the country. Results suggested that the dry conditions were related to a northward extension of positive 500 hPa height anomalies over the continental U.S. that persisted for several seasons. However, further research into this possible link is required (Bonsal and Wheaton, 2005).

Several studies have examined large-scale causes of major drought episodes over the mid-western U.S. These investigations have highlighted a number of potentially important factors contributing to the dry conditions including extra-tropical and tropical Pacific SST anomalies, soil moisture, changes in storm tracks and links with adjacent Pacific and Atlantic anticyclones (e.g., Trenberth et al., 1988; Ting and Wang, 1997; Schubert et al., 2004a). In addition, the recent 1998 to 2002 extreme drought over most of the U.S. and the 1930s dust bowl over the U.S. Great Plains have been attributed, in part, to La Niña-like conditions in the tropical Pacific (Hoerling and Kumar, 2003; Schubert et al., 2004b). Although a few of these relationships likely apply to Canada, it appears that some of the identified causes differ from those associated with western Canadian droughts. This signifies that further research is required to determine the large-scale causes of extended dry periods over interior North America including possible differences between northern and southern portions of these mid-continental regions.

Droughts tend to persist in that warm, dry springs are followed by hot, dry summers. There also appears to be a tendency for warm summers to follow other warm summers, and so on. Reasons for this are likely related to feedback processes that enhance or prolong drought situations (e.g., soil moisture anomalies) (Maybank et al., 1995). The concept that drought begets drought was first proposed by Namias (1960) who suggested that dry conditions in spring favour the formation of anticyclonic pressure conditions, thus perpetuating dry conditions for a season or longer. Fennessy and Sud (1983) suggested that large-scale, prolonged droughts may be partially maintained by the feedback influence of soil moisture on rainfall. Further substantiation of this hypothesis was provided by Oglesby and Erickson (1989) who found that a reduction of soil moisture in the U.S. Great Plains leads to higher surface temperatures, lower surface pressures, increased upper-atmospheric ridging, and a northward shift of the jet stream. They therefore concluded that soil moisture played an important role in prolonging and amplifying summer drought. An extension of this study found that whereas late winter – early spring soil moisture had little effect beyond a couple of weeks, a late spring anomaly could have a significant effect on the ensuing summer (Oglesby, 1991). While these studies have focussed on the U.S. Great Plains, there is good reason to believe that they also apply to the Canadian Prairies.

Future Droughts

All Global Climate Models (GCMs) are projecting future increases of summer continental interior drying and associated risk of droughts. The increased drought risk is ascribed to a combination of increased temperature and potential evapotranspiration not being balanced by precipitation (Meehl and Stocker, 2007). A first-order assessment of future drought occurrence over southern Canada by Bonsal and Regier (2006) (Figure 2) indicates small positive changes in SPI over all of southern Canada for the majority of climate-change scenarios. This is attributable to the fact that future annual precipitation is projected to increase over most of southern Canada. The PDSI findings, however, reveal dramatic increases to the potential for future droughts particularly, in the warm-dry scenario. Differences between the SPI and PDSI can be attributed to the PDSI's inclusion of temperature in its calculation. All scenarios project considerable increases to temperature and in general, small increases to precipitation over southern Canada. The higher temperatures translate into greater evaporation and more severe droughts. Since the SPI only takes into account precipitation, droughts using this index are not projected to become more severe in the future. It should also be pointed out that considerable uncertainty exists with respect to future precipitation, particularly on a regional and intra-seasonal basis. Furthermore, relatively little is known regarding changes to large-scale circulation and since these patterns have a significant impact on temperature and precipitation over Canada, the occurrence of future drought remains a huge knowledge gap.

Monitoring, Modelling, and Prediction

Numerous indices that are measures of drought severity are used for the monitoring and modelling of drought. These range from simple approaches that only consider precipitation (e.g., SPI), to more complex indices that incorporate a water balance approach using precipitation, potential evapotranspiration, antecedent soil moisture and runoff (e.g., PDSI). Various indices have also been used to monitor and model soil moisture changes from daily precipitation and actual evapotranspiration. A problem with these more complex indices is that evapotranspiration is difficult to compute since it relies on meteorological measurements that are generally not readily available (net radiation, vapour pressure deficit, wind speed). The high spatial variability of summer convective rainfall and difficulties in modelling snowmelt and blowing snow also hinder regional-scale moisture modelling (Maybank et al., 1995).

Real-time reports of lake and reservoir levels, stream flows, snowpack, water-supply volume forecasts, dugout water levels (for the Prairies), precipitation, and various drought indices are currently used for drought monitoring in Canada. The status of these water supplies is critical for activities such as irrigation, water apportionment, storage, flood forecasting, hydro-electric power generation, navigation, fisheries, and wetland habitat. In the Canadian Prairies, provincial water resource agencies have been publishing monthly reports of stream, lake, reservoir, and groundwater levels since the late 1970s. For Canada, real-time information on pasture conditions, on-farm surface water supplies, and several drought indices are provided in Agriculture and Agri-Food Canada's *Drought Watch* web site (*http://www.agr.gc.ca/pfra/drought/default.htm*). The site monitors the risk and status of drought over major agricultural regions of the country by providing national and regional maps of temperature, precipitation, SPI, PDSI, and soil moisture for various time periods. It also promotes practices to reduce drought vulnerability. Recently, the North American Drought Monitor

http://www.ncdc.noaa.gov/oa/climate/monitoring/drought/nadm/

was established as a cooperative effort among drought experts in Canada, Mexico, and the U.S. to monitor drought across the continent on an ongoing basis. The Monitor provides continental maps that aid in assessing and communicating the state of drought over North America on a weekly basis. The maps are based on a process that synthesizes multiple indices, outlooks and local impacts, into an assessment that best represents current drought conditions.

Satellite and radar measurements can potentially provide solutions to the spatial-scale problems associated with drought monitoring and modelling. The Meteorological Service of Canada currently uses Special Sensor Microwave Imager (SSMI) to produce snow water equivalent maps for the Prairie provinces that are made available to water resource agencies.

Drought prediction involves anticipating climatic anomalies that produce unusually dry conditions for an extended period of time. However at present, there is no completely satisfactory method that can routinely predict Canadian climate over the month to season time frame required for drought analysis. Environment Canada currently produces three-month deterministic temperature and precipitation forecasts for the ensuing 1-3, 2-4, 4-6, 7-9, and 10-12 month periods. The 1-3 and 2-4 month forecasts are based upon an ensemble of 40 model runs using the Climate version of the Global Environmental Multiscale model (GEM-CLIM), the second generation of the Atmospheric General Circulation Model (AGCM2), the third generation of the Atmospheric General Circulation Model (AGCM3), and the Spectral aux éléments finis (SEF) model. Probabilistic forecasts, which give estimates of the probability that the seasonal mean will be above, near, or below normal are also provided for the 1-3 and 2-4 month periods. Forecasts for the 4-6, 7-9 and 10-12 month periods are produced with a statistical method and do not use ensemble forecast technique. The forecasts are updated on a monthly basis.

Adaptation

Adaptation involves adjusting to climate change, variability, and extremes in order to avoid or alleviate negative impacts and benefit from opportunities. Drought adaptations include short to long-term actions, programs, and polices implemented both during, and in advance of the drought to help reduce risks to human life, property, and productive capacity (Wilhite, 2000). Canadians have a great deal of experience in adapting to droughts; however, their strategies vary by sector and location. Areas with greater drought risks are often better prepared to deal with dry conditions. Drought adaptation decisions are made at a variety of levels ranging from individuals, to groups and institutions, to local and national governments. There are various adaptation processes or strategies including sharing and/or bearing the loss, modifying drought effects, research, education, behavioral changes, and avoidance (Burton et al., 1993). Adaptive drought measures include soil and water conservation, improved irrigation, the construction of infrastructure (wells, pipelines, reservoirs), and the exploration of groundwater supplies. The usefulness of these strategies varies with location, sector, and nature and timing of the drought. Better management responses may be made with improved drought monitoring and advanced prediction. Adjustments that occur after the drought are generally less effective compared to planned anticipatory adaptation.

Drought adaptation research and planning strategies are in their early stages although risk management plans for drought prone regions of the country have been established (e.g., Agriculture Drought Risk Management Plan for Alberta). Many adaptive strategies have been devised and tested for their effectiveness in reducing drought impacts (Maybank et al., 1995). However, intense, large-area droughts that persist for several years still result in severe hardship to even those regions used to coping with droughts. An improved capability to estimate the numerous impacts associated with drought is required for enhanced adaptation. Future national, provincial, and municipal level coordinated and proactive drought planning is also needed since vulnerability to future droughts could be exacerbated by increasing development, and the increased risk of drought that is projected to occur over most mid-latitude continental interiors as a result of climate change.

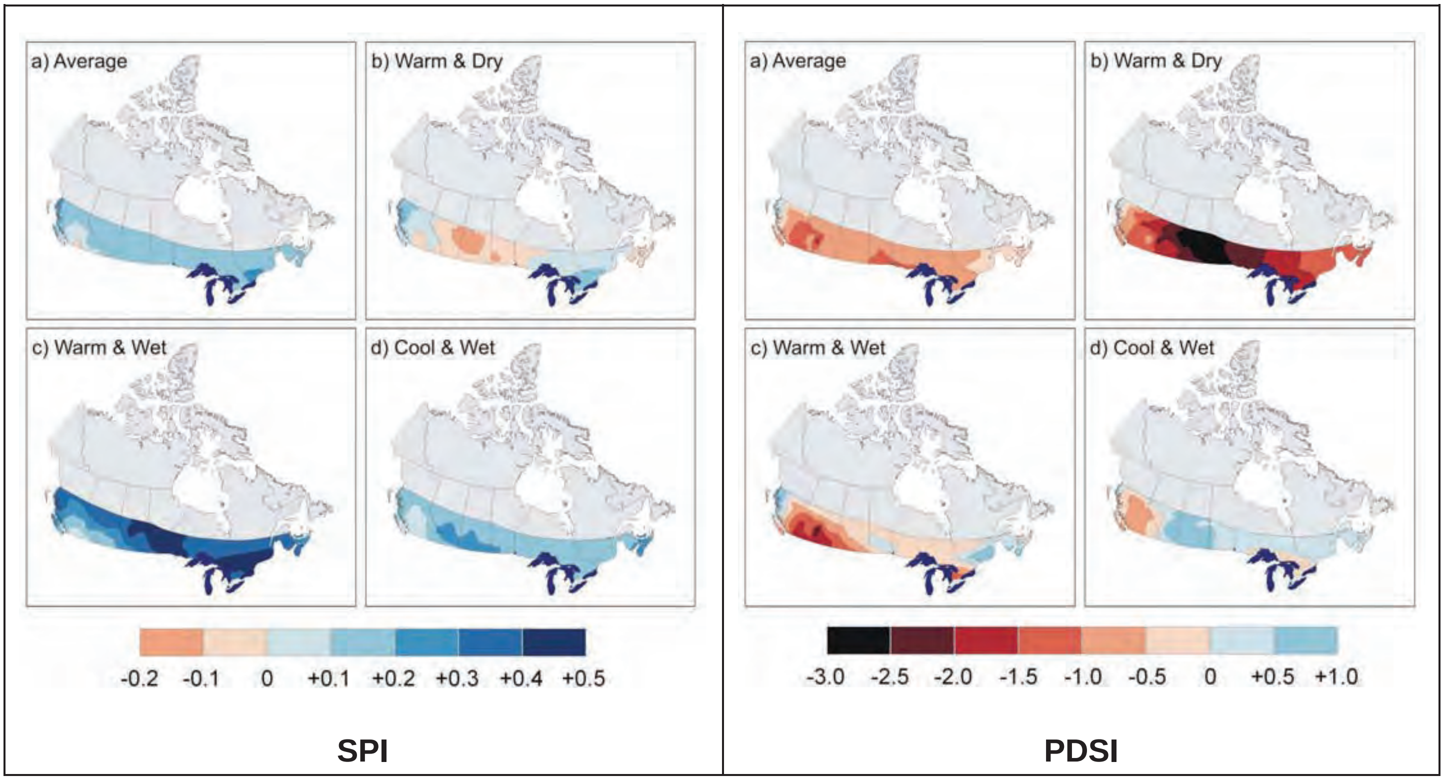

Figure 2: Projected average changes in SPI and PDSI values over southern Canada based on a) average, b) warm and dry, c) warm and wet, and d) cool and wet climate-change scenarios. The scenarios are based upon 30-year projected changes in temperature and precipitation for the period 2041-2070 (relative to the 1961-1990 baseline) using the A2 and B2 emission scenarios from multiple GCMs. Maps provide agricultural year (September to August) SPI and PDSI changes (from Bonsal and Regier, 2006).

Knowledge Gaps and Program Needs

There are several gaps in the knowledge of droughts that limit our ability to understand their occurrence, monitor/model their status, and adapt to their negative effects. The following identifies major research and program needs regarding droughts in Canada.

1) Drought Occurrence

A better understanding of the physical causes and characteristics of past droughts including their spatial and temporal variability is required. This will provide improved insight toward short-term (seasonal to annual) and long-term (decade to century) projections of future droughts in Canada. In particular, we require:

■ Improved knowledge of drought trends and variability prior to the instrumental record. This requires more research into reliable proxy indicators to reconstruct drought occurrence over various regions of Canada for the last few hundred years.

■ An improved understanding of the physical causes of drought initiation, persistence and termination during the last few hundred years. This includes:

a) The role of large-scale atmospheric and oceanic oscillations in the initiation and persistence of anomalous circulation patterns responsible for drought, particularly during the summer season;
b) The impacts of soil moisture anomalies on the perpetuation and migration of drought;
c) The physical causes of multi-year droughts and their recurrence on decadal time scales;
d) The atmospheric circulation patterns associated with unusually large spatial-scale droughts (e.g., the 2001 drought over most of southern Canada);
e) The atmospheric conditions responsible for the termination of a drought including aspects such as convective rainfall, precipitation trigger mechanisms and moisture sources.

■ Better knowledge regarding the occurrence of future droughts in terms of likely areas to be affected and potential changes to their frequency, duration, and severity. This requires:

a) More reliable future climate simulations (particularly precipitation) from Global and Regional Climate Models;
b) Improved downscaling methods for the application of climate model data to the appropriate spatial and temporal scales;
c) Knowledge of future changes to large-scale circulation patterns and oscillations such as ENSO, PDO and the NAO.

2) *Monitoring, Modelling, and Prediction*

The ability to more accurately predict drought onset, intensity, and termination requires improvements in the modelling and monitoring of current drought conditions, as well as, better seasonal climate forecasts. The following are needed to improve our capability to monitor, model and predict Canadian droughts:

■ Development of a total water supply database including for example, improved data of stream flow records, wetland numbers and groundwater supplies.

■ Development of an index or combination of indices to monitor past and near real-time drought conditions and to aid in the recognition of drought sufficiently in advance. Standard indices would allow for national-scale evaluations of drought.

■ A better understanding of the amount and distribution of groundwater resources including the linkages to climate and surface water supply.

■ Development of better methodologies to incorporate remote sensing and ground-level radar for drought monitoring and management (to augment the climate station network). The geospatial and temporal capacity of satellite imagery offers many opportunities for advanced monitoring capabilities.

■ The incorporation of existing Geographical Information System (GIS) techniques to provide better spatial representations of drought. For example, the migration patterns of drought and its associated synoptic circulation patterns could be tracked on a variety of temporal scales.

■ Better hydrologic modelling techniques and in particular, improved methodologies to estimate evapotranspiration.

■ Improved integration of Global and Regional Climate Models with distributed water balance models in order to model future drought conditions.

■ More reliable short-term (seasonal) forecasts of temperature and precipitation at the appropriate spatial scales to aid in the prediction of drought onset, intensity, persistence and termination.

3) Impacts and Adaptation

Droughts are certain to recur in the future. As a result, more effective short and long-term adaptation strategies are required to defend against these future droughts including improved technological, monitoring and predictive capabilities. Additional requirements include:

■ More rapid updates of potential drought conditions to activate drought response and adaptation options.

■ The identification of ecosystem and economic thresholds to determine at what point during a drought adaptation options need to be activated to avoid serious or irreversible losses.

■ More research into the understanding and modelling of drought adaptation measures, including their effectiveness, practicality, costs and benefits.

■ Improved knowledge regarding adaptation to prolonged droughts including those that may result due to climate change.

■ Better abilities to adequately assess the socio-economic consequences of alternative drought adaptation strategies.

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Prochain numéro du *CMOS Bulletin SCMO*

Le prochain numéro du *CMOS Bulletin SCMO* paraîtra en **août 2008.** Prière de nous faire parvenir avant le **4 juillet 2008** vos articles, notes, rapports d'atelier ou nouvelles à l'adresse indiquée à la page ii. Nous avons un besoin URGENT de vos contributions écrites.

A Drought Research Initiative for the Canadian Prairies

Ronald Stewart[1], John Pomeroy[2] and Rick Lawford[3]

Résumé: Les Prairies sont souvent exposées à la sécheresse et quelques fois de façon catastrophique. La plus récente sécheresse a eu lieu au cours de l'épisode 1999 à 2005, et elle a produite des conditions les plus sèches du dossier historique. Pour traiter de telles sécheresses, un réseau de recherche du nom de DRI (Drought Research Initiative – Initiative de recherche sur la sécheresse) a été formé. Le centre d'intérêt particulier du réseau DRI consiste à mieux comprendre la façon dont les sécheresses surviennent, évoluent et prennent fin afin de comprendre leur structure interne et de contribuer à une meilleure prédiction de tels événements. Afin de réaliser cet objectif, on considère la sécheresse sous différents points de vue en tenant compte de l'atmosphère, du sol incluant les processus de la végétation et du sous-sol. Cette sécheresse fut exceptionnelle de telle sorte que son processus à grande échelle a été assez variable dans le temps. De plus, on a noté que les nuages étaient fréquents et qu'à travers les Prairies il est arrivé de voir quelques fois, de façon simultanée, des records de grosses précipitations dans certaines régions. Pourtant, cette sécheresse a produit quelques-unes des plus grandes diminutions de l'humidité enregistrée en profondeur et a contribué à une diminution majeure de l'écoulement des rivières. De plus, la communauté de recherche du réseau DRI, à travers le Canada, travaille étroitement avec plusieurs partenaires concernés par la sécheresse et qui ont tous intérêt à faire face à de tels événements, dans le futur. Cet article résume l'Initiative de recherche sur la sécheresse en faisant valoir les caractéristiques de la récente épisode de sécheresse, ainsi que les objectifs du réseau DRI, les enjeux scientifiques clés, les récents progrès et les plans futurs.

1. Background

The occurrence of drought is a ubiquitous feature of the global water cycle. Such an extreme does not necessarily lead to an overall change in the magnitude of the global water cycle but it of course affects 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 lack easily identified onsets and terminations.

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

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 agricultural areas of the Canadian Prairies are therefore prone to drought.

Droughts in the Canadian Prairies are distinctive in North America. The large scale atmospheric circulations are influenced by blocking from major orographic features 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 a relatively long snow-covered season and short growing season; local surface runoff is primarily produced by snowmelt water; and the landscape has substantial water storage potential in the poorly drained, post-glacial topography; and aquifers are overlain by impermeable glacial till, but there are also important permeable aquifers in surficial deposits that have substantive water exchange with the surface.

One example of Prairie drought is the recent multi-year event that began in 1999 with cessation of its atmospheric component in 2004/2005 and many of its hydrological components in 2005. This event produced the worst drought for at least a hundred years in parts of the Canadian Prairies. An illustration of the severity is shown in Figure 2 for the 2000/01 agricultural year. This multi-year drought led to major impacts across the Prairies as discussed by Lawford et al. (2008).

Despite enormous economic, environmental, and societal impacts of drought, there has never been a coordinated and integrated drought research program in Canada. Given the importance of this extreme form of weather, it is critical that it be studied appropriately with the hope being that its occurrence and nature can be better anticipated on short and long term scales.

The purpose of this article is to provide a brief overview of a **D**rought **R**esearch **I**nitiative (DRI).

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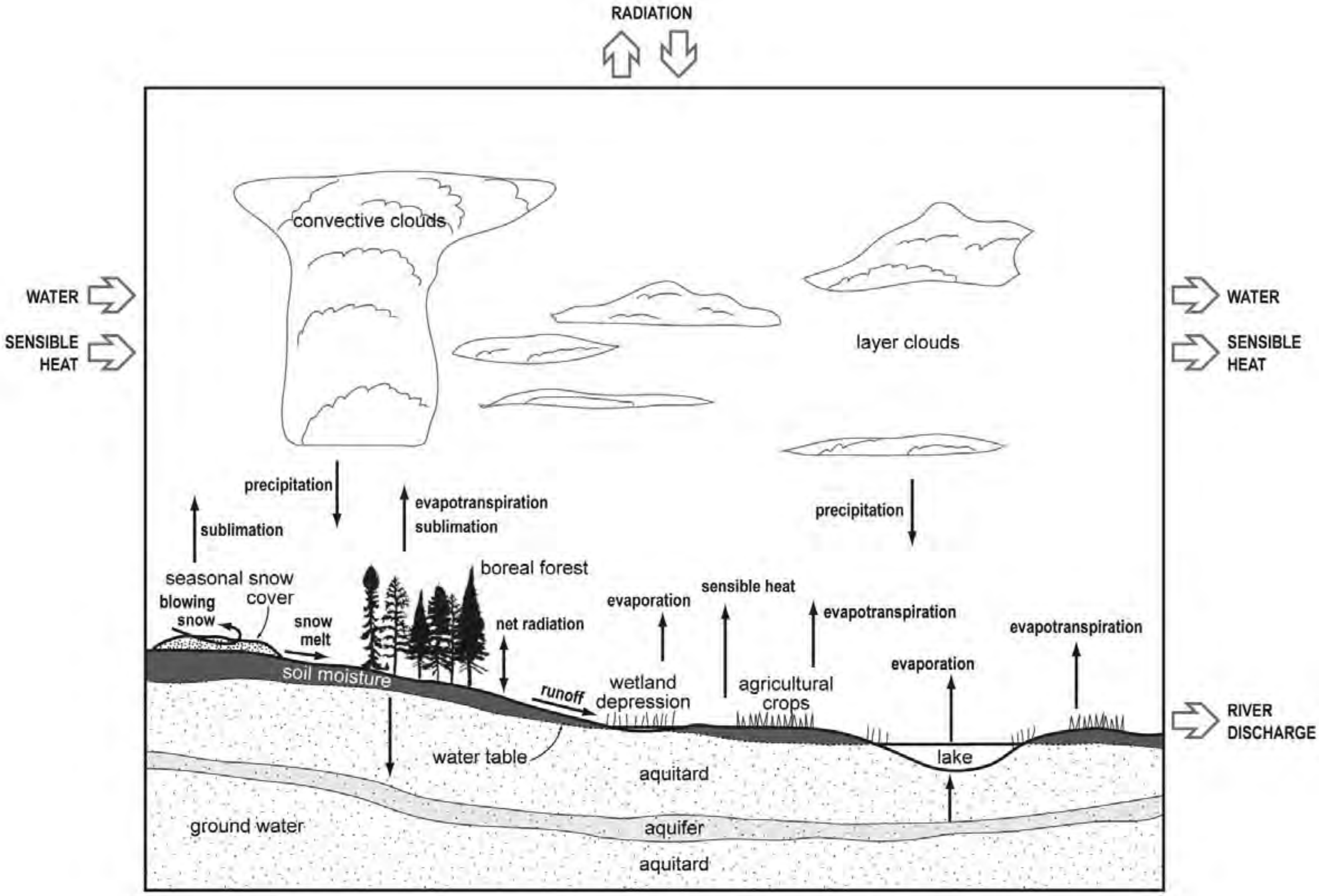


Figure 1. Water and energy cycling associated within Canadian Prairie drought.

2. Objectives

To begin to address these issues related to drought, the Drought Research Initiative, DRI was established. DRI is a research network largely funded by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS).

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 is focused on five research objectives:

1) To quantify the physical features of this recent drought;

2) To improve the understanding of the processes and feedbacks governing the formation, evolution, cessation and structure of the drought;

3) To assess and reduce uncertainties in the prediction of drought and its structure;

4) To compare the similarities and differences of the recent drought to previous droughts over this region and those in other regions, in the context of climate variability and change; and

5) To apply our progress to address critical issues of importance to society.

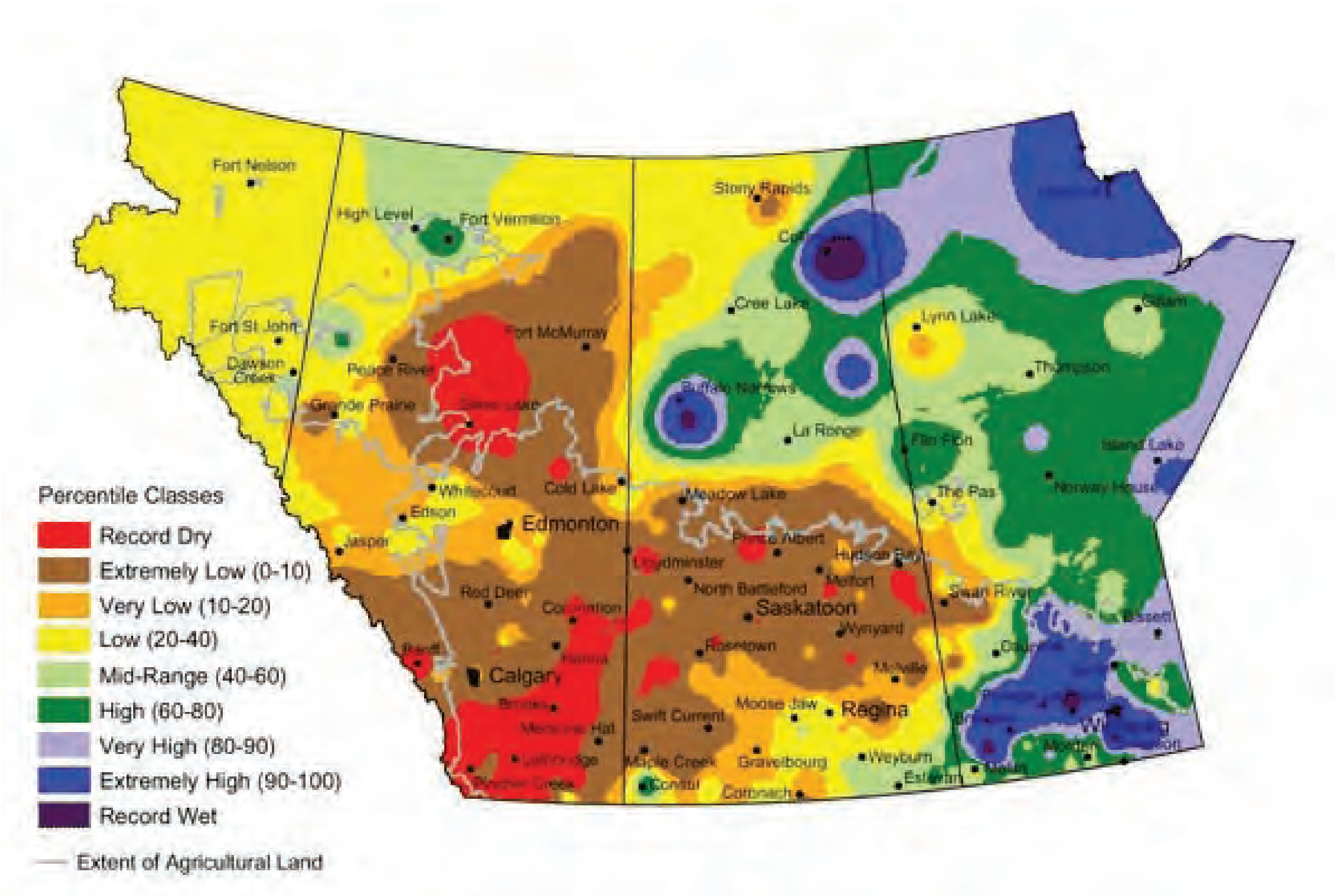


Figure 2. Example of the precipitation deviation from normal in the early drought period, September 1, 2000 - August 31, 2001. Courtesy of Prairie Farm Rehabilitation Administration.

DRI brings together many university and federal/provincial government researchers to address this issue with expertise encompassing the atmospheric, hydrologic, land surface and predictive aspects of droughts at a variety of spatial and temporal scales. As shown in Table 1, DRI is overseen by a Board of Directors, its scientific effort is driven by a Science Committee and its researchers have either CFCAS funding (investigators) or are carrying out contributing research through other means (collaborators). It should be noted that only Objectives 1-3 were able to be funded directly through CFCAS; objectives 4-5 are being addressed using other funds and linkages to the extent possible. Lawford et al. (2008) discusses the critical DRI Partners Advisory Committee that gives guidance directly to the Board of Directors.

To make progress on this critical issue over the 5-year period of a CFCAS Network, the project focuses, although not exclusively, on the recent drought over the Prairies. This drought was by far the best observed and modelled one over this region and its impacts are still fresh in people's memory. This strategy, a focus on physical processes and particular time periods or events, is a common one although not so for drought. For example, it has been applied successfully for IPY (International Polar Year) and for MAGS (Mackenzie GEWEX Study) which used it to examine a year with record low discharge from the Mackenzie River (Stewart et al., 2002). The assumption is that, in general, it is 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 the case of DRI, one can even consider the focus on 1999-2005 drought as being a 'pilot' project for drought research including strong interactions with those affected by it.

From a longer-term perspective, it is envisioned that this 5-year Network represents an essential step towards 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 issues directly address major issues for society. There needs to be better guidance on the likelihood of drought including 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 this has to be our ultimate objective; to better assess the likelihood of such a scenario. With this Network, we will be moving systematically towards these two objectives.

3. Strategy

As outlined in Section 2 above, DRI will achieve 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 comparisons of our findings with other droughts as well as the implications for society.

3.1 Theme 1

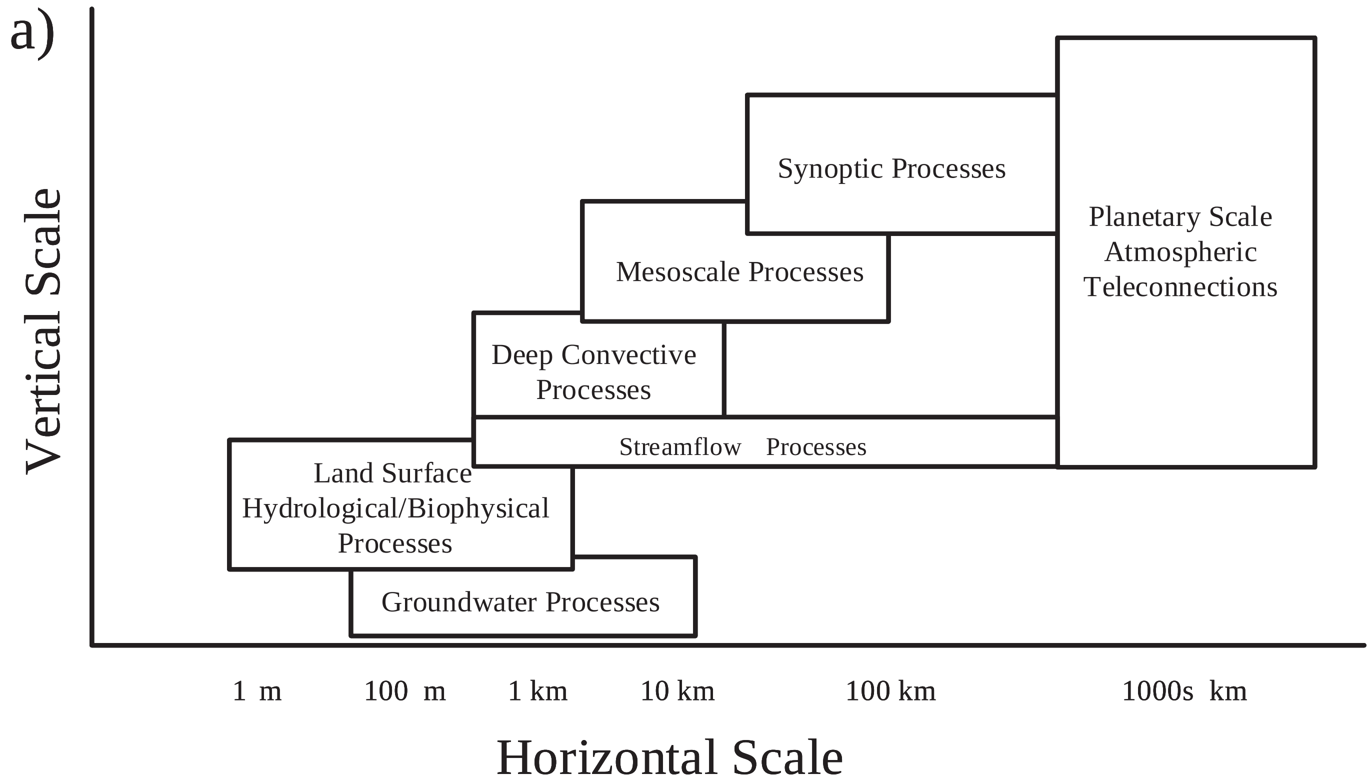
The first step towards the better understanding of the 1999-2005 drought involves the quantification of its atmospheric, hydrologic and land-surface physical features at a variety of spatial and temporal scales. As the drought is being quantified, this information forms much of the basis of Themes 2 through 5.

Theme 1 is being realized through three focussed questions:

- 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 addressed. 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, pressure, wind, clouds and precipitation amount. 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 are also an important long-term indicator of drought. 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 be drained to streams. Proper characterization of depression storage is essential for understanding the hydrology of the prairie region. It is not easy to acquire the needed observational information. First, there is operational instrumentation across the region that in some cases is arranged as networks. This includes weather stations, radars, lightning detectors, stream gauges, lake levels, vegetation assessment, crop yields, snow information, soil moisture and ground water. In general, though, there are relatively few of these sites. Others though have used some of these data in order to make gridded products that are extremely useful for characterizing drought. One example of this is the CANGRID precipitation information based on station information that has been homogenized and adjusted for all known measurement errors (Mekis and Hogg, 1999; Vincent and Gullett, 1999). Second, satellite-based observations are extremely important and they 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 snowcover and vegetation, down to sub-surface water storage. Not all of the products are adequate however and many have limitations on temporal and spatial resolution. Third, there are a few locations (Figure 3) at which a large number of detailed measurements are carried out. This includes BERMS (Boreal Ecosystem Research and Monitoring Sites) in northern Saskatchewan, the St. Denis Wildlife area near Saskatoon, and the Assiniboine Delta Aquifer in western Manitoba. The types of data at these sites is not consistent though with some, for example, having a number of atmospheric-related measurements and others focused on surface and sub-surface variables. Fourth, some individual researchers have acquired their own unique field measurements. There is a wide variety of this information and much of it can be accessed through contacting the researcher directly.

Model products are being used to fill gaps in the observational record. These data sets include GEM (Global Environmental Multiscale model), ECMWF (European Centre for Medium range Weather Forecasting), CRCM (Canadian Regional Climate Model, and CCCMA (Canadian Centre for Climate Modelling and Analysis) to name a few. Each of these models has its own spatial and temporal resolution, from coarse spatial scales (of order a few hundred kilometres) to shorter mesoscale ones (a few tens of kilometres).



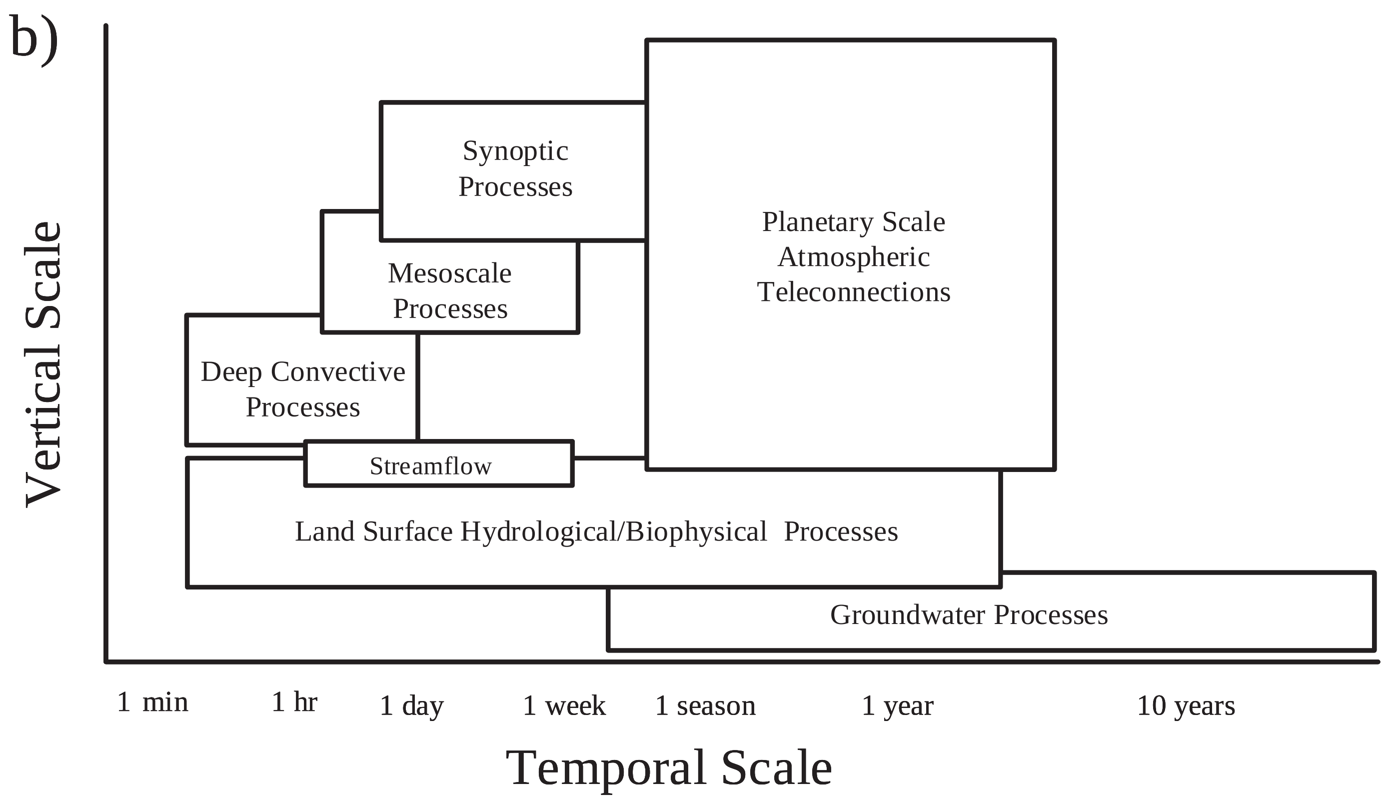


Figure 3: (a) Spatial and (b) temporal scales of processes associated with Prairie droughts. Note that 'mesoscale' refers to the atmospheric processes including the precipitation associated with frontal systems.

Hydrological and surface models are essential to DRI. Ones being used and/or improved extensively include MESH (MEC [Modélisation Environmentale Communautaire] Surface and Hydrology model interfacing with the GEM model), VIC (Variable Infiltration Capacity model), CRHM (Cold Regions Hydrological Model), SABAE-HW (Soil Atmosphere Boundary, Accurate Evaluations of Heat and Water), and CLASS (Canadian Land Surface Scheme). This effort includes coupling of surface and sub-surface water conditions.

Furthermore, the fluxes and budgets of water and energy through and within the Prairies during drought must be addressed. This needs to be accomplished through the analysis of the model and observational products described above. This DRI-wide activity is being addressed 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.

3.2 Theme 2

Given that the 1999-2005 drought and its features are being quantified in Theme 1, the next issue is to better understand the processes and the feedbacks responsible for the drought's initiation, persistence, and termination. This theme is addressing 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 being devoted to better understanding processes and feedbacks. This recognizes that there has been relatively little attention paid to the mechanisms directly associated with Canadian drought. Prairie drought processes have characteristic spatial and temporal scales; these are shown in Figure 3. We hypothesize that atmospheric circulation patterns normally induce the onset of drought, but its termination is also linked with land surface and groundwater conditions as well as atmospheric conditions. It is also important to note that land surface hydrological/biophysical processes generally operate at small spatial scales (and with large 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 scales 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.

It also needs to be recognized that there are many ways in which drought, basically a sustained precipitation deficit, can be prolonged. Some of the ways to reduce precipitation include, for example, large scale circulation anomalies, lack of moisture advected into a region, reduction of local moisture supplies, reduction of vegetation for evapotranspiration, reduction of sub-surface water supply for evaporation, production of virga as opposed to precipitation, and possibly even the role of aerosols in the dusty environment. Over the 5+ years of the drought, it is anticipated that all these, and numerous other factors, were operating at various times and locations to suppress the production of substantial precipitation.

3.3 Theme 3

Given that the 1999-2005 drought and its features are being quantified and the fundamental responsible processes better understood, the next issue is to assess and improve predictive techniques for it. The modelling tools used are global and regional climate models (GCMs and RCMs), and hydrological models. The hydrological models will be driven by output from the atmospheric models and observations from research sites and available reanalysis data. Atmospheric modelling spans scales from global to regional to watershed scales characteristic of the prairies, while hydrological modelling is accomplished using a hierarchy from small scale detailed process models to large scale models run over river basins. The major questions are:

- 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 will largely be made of archived information to address many of these issues. This, for example, is available from the Historical Forecast Project that addressed seasonal prediction as well as from operational seasonal forecasts of Environment Canada. DRI-related research is focussed on a particular extreme and examines many more variables than the traditional analysis of temperature and precipitation. As discussed under Theme 2, there are many ways in which a precipitation deficit arises and these need to be considered when analyzing prediction results. It is also expected that experiments will be carried out within DRI for assessing the role of soil moisture and perhaps snowcover on seasonal prediction.

3.4 Theme 4

Given that the 1999-2005 drought and its features are being quantified, better understood, and potentially better predicted, the next issue is to compare our progress with droughts occurring at other times and locations. The objectives of Theme 4 will be 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) US 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 others based on circulation patterns and climate variables. To carry out comprehensive comparisons, however, these analyses have to be extended to include many more variables in the atmosphere and surface. Furthermore, these analyses have to examine the internal structure of drought, not just its presence over a particular region. Many droughts, including the one in 1999-2005, illustrate a complex, dynamic, internal structure of precipitation and possibly other variables, and the pattern changed dramatically during the drought. Such internal features can in some instances be just as important as the general occurrence of drought.

3.5 Theme 5

Theme 5, addressing the societal impacts of drought, can be broken down into sub-issues which include:

- What organizations are affected by drought?

- What is the nature of the drought's impact and how can these impacts be alleviated?

- Given the progress being made by DRI, how can it enable organizations affected by drought impacts to respond more effectively in the future?

A major portion of this effort is described in Lawford et al. (2008). This Theme relies heavily on the active two-way involvement of the partners. Progress being made by DRI needs to be conveyed to impacted groups and vice versa. In turn, impacted groups through this Theme inform the Network on critical issues, thresholds and other factors relating to drought, enabling DRI research to adjust and thereby more effectively address the concerns of Canadians.

4. 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 is focussing on the entire 'system' during periods of extreme dryness. Even though there are several international and, to a lesser extent, national programs that have addressed extremes in the water cycle, DRI fills a niche because none have specifically focused on the Canadian Prairies.

4.1 Canadian Linkages

On a research level, the Network has already linked several university-based researchers from institutions in Canada as well as a number of federal and provincial agencies and departments. At the federal level, it has also established collaborative links with several departments including several components of Environment Canada, Agriculture and Agri-Food Canada, and Natural Resources Canada. DRI has also established close links with Canadian GEO (Global Earth Observations) which is keenly interested in drought. DRI is exploring the feasibility for being a test-bed for their pilot projects and long-term plans.

DRI has established many linkages at the provincial level. Within the Prairie provinces this includes the 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; and the Saskatchewan Research Council. Linkages also include the Prairie Provinces Water Board which considers water flows across provincial boundaries. Links have also been established with Ouranos, the Québec-based initiative concerned with regional climate.

The Network complements previous or current Canadian research studies. This includes the Mackenzie GEWEX Study (MAGS) that was concerned with Mackenzie basin water and energy cycle issues (Stewart et al., 1998), and Canadian CLIVAR activities that considered climate variability (Derome et al., 2004). DRI also has 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).

Although DRI can link with other Canadian activities, it is unique and fills an important gap. No other activity is addressing head-on the critical multi-disciplinary drought issue that regularly affects the Canadian Prairies.

4.2 International Linkages

Internationally, DRI has its strongest linkages with 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 will be developed with organizations and individuals studying American droughts. There is, for example, a natural link with the GEWEX America Prediction Project (GAPP where GEWEX is the Global Energy and Water Cycle Experiment) which in turn is part of CPPA (Climate Prediction Program of the Americas). The Network will also interact with the U.S. Drought Mitigation Center, the North American Drought Monitor, and US CLIVAR activities.

DRI is also contributing to and taking advantage of research over other parts of the world. For example, both the World Climate Research Programme (WCRP) and GEWEX through it Coordinated Energy and water cycle Observation Project (CEOP) have recently initiated activities focussing on extremes such as droughts. The work in DRI is contributing directly to this and, to some degree, it is considered to be a model as to how one addresses extremes in a comprehensive manner.

Other collaborations will include the International Decade for Predictions in Ungauged Basins 2003-2012 (PUB), a hydrological decade for improving the understanding and prediction of hydrological systems where surface observations are not available for model calibration (Sivapalan et al., 2003). A particular emphasis of PUB is on hydrological prediction in semi-arid to sub-humid zones. Through exchange of techniques and information, DRI will both contribute to and benefit from links to PUB. The Network will continue links to the International Water Management Institute (IWMI) in its studies of drought assessment and mitigation in southern Asia; the IWMI currently uses Canadian water assessment methodologies in some of its hydrology studies

http://www.iwmi.cgiar.org/drought assessment/index.asp

The region has certain similarities to the Prairies in that snowmelt-fed mountain waters supply much of the water to a semiarid and sub-humid lowland region.

5. Progress and Update

DRI is midway through its activities. Substantial progress has been made on many fronts. A few illustrations of progress are mentioned here.

DRI has brought together an unprecedented amount of information on Canadian drought. On its web site

http://www.drinetwork.ca

one can find many links to various datasets that describe elements of drought in the atmosphere, at the surface or below the surface. Compiling a Prairie-wide database of provincial groundwater and water levels is part of this effort. This collective progress is in itself a major accomplishment. Now the task is to ensure that as much of this information as possible is integrated and made even more accessible. A synthesis article characterizing the 1999-2005 drought is in progress and this will be followed by another one addressing the water and energy budgets during the drought. In addition, new techniques of archiving and making available datasets are being explored as another legacy of DRI.

Tremendous progress has been made in examining the multitude of processes that operated during the drought. As discussed by Bonsal (2008) large scale factors illustrated consistencies with and differences from those associated with other droughts. However, a host of other atmospheric, surface and sub-surface processes including evapotranspiration, runoff generation and sub-surface water transport are also being studied and these can all affect the nature of drought. All of these issues will be brought together in a dedicated workshop over the next year to ensure that we have collectively addressed this key issue. This workshop will build on a successful evaporation workshop that was held in 2007.

There had not been a systematic study before of the capability of season-prediction systems to anticipate drought. This is currently underway within DRI although, in general terms, it appears that key aspects of the drought's persistence and end were not well-anticipated. In addition, it is recognized that initialization of these models with surface conditions (soil moisture, snowcover) may well improve predictive capabilities. Initial experience with these is anticipated by the end of DRI. Some of this work is being carried out in cooperation with GOAPP (Global Ocean-Atmosphere Prediction and Predictability, another CFCAS-sponsored Network). A dedicated workshop on this issue has been held and this activity will also work with our US colleagues to ensure as much progress as possible.

Largely through other funding beyond that of CFCAS, a number of researchers are able to carry out comparison studies. Bonsal (2008) has noted a number of differences and similarities at large scales for example between this recent drought and others. Much more needs to be done on this issue to apply our detailed knowledge of one drought to other, less well-understood ones. A dedicated workshop on this issue will be held in the last year of DRI with the intent being to apply our knowledge of the 1999-2005 drought to others and to place this drought into a larger context, including the extent to which it might be the harbinger of future drought over this region.

As mentioned earlier in this article, strong interactions have developed with those affected by drought. To move this along as efficiently as possible, the DRI Partners Advisory Committee was established, as discussed by Lawford et al. (2008). This Committee is, for example, organizing, funding permitted,'a simulation exercise' in which experiences from DRI are presented as if corresponding to a future drought. Such a learning experience will include both researchers and partners.

It should also be noted that there are many students working within DRI. These students are enjoying a unique opportunity to contribute to our knowledge of drought as well as to gain a wide perspective on the many issues linked with this phenomenon. The training of these students represents an important DRI legacy.

Table 1: DRI Board of Directors, Investigators and Some of the DRI Collaborators. Science Committee members are indicated by * and Theme Leads by “t”. The number of collaborators continues to grow.

Board of Directors	**Jim Bruce** - - Chair	
	Gary Burke - - Member (Environment Canada)	
	Harvey Hill - - Member (Agriculture and Agri-Food Canada)	
	John Pomeroy - - Member (DRI Science Committee Co-Chair)	
	Ron Stewart - - Member (DRI Science Committee Co-Chair	
	Tim Aston - - Ex-Officio (CFCAS)	
Investigators	***t Barrie Bonsal** (Saskatchewan)	*** John Pomeroy** (Saskatchewan)
	Paul Bullock (Manitoba)	*** Ken Snelgrove** (Memorial)
	John Gyakum (McGill)	*** Ron Stewart** (McGill)
	***t John Hanesiak** (Manitoba)	**Geoff Strong** (Alberta)
	***t Masaki Hayashi**	**Garth van der Kamp** (Saskatchewan)
	Henry Leighton (McGill)	***t Elaine Wheaton** (Saskatchewan)
	***t Charles Lin** (McGill)	*** Al Woodbury** (Manitoba)
	Al Pietroniro (Saskatchewan)	
Collaborators	**Aaron Berg** (Guelph)	**Amir Shabbar** (EC)
	George Boer (EC)	**Dave Sills** (EC)
	Daniel Caya (Ouranos)	**Susan Skone** (Calgary)
	Jacques Derome (McGill)	**Craig Smith** (EC)
	Raoul Granger (EC)	*** Kit Szeto** (EC)
	Ted Hogg (NRCan)	**Brenda Toth** (EC)
	Bob Kochtubajda (EC)	**Jessica Toyra** (EC)
	Rick Raddatz (Manitoba)	**Alex Trishchenko** (NRCan)
	Hal Rithcie (EC)	**Anne Walker** (EC)
	Alonso Rivera (NRCan)	**Shusen Wang** (NRCan)
	Dave Sauchyn (Regina)	

6. Summary

Drought is a huge issue for Canada and DRI is addressing it in a comprehensive manner for the first time. This collaborative effort is providing a better understanding of the physical features of Prairie drought, the processes controlling it, and the capabilities to predict it. DRI is also comparing the recent drought with other earlier Prairie ones and with those occurring elsewhere; which will lead to a more complete picture of the implications for droughts occurring across Canada. Furthermore, interactions with the user community have been established so that DRI's progress contributes directly to these groups and their guidance influences research plans.

DRI is carrying out fundamental research on a climatic extreme but it is also targeted research. Given this reality, at the conclusion of the Drought Research Initiative in December 2010 we expect to say that:

“*We have greatly increased our understanding of drought through a focus on the recent 1999-2005 one over the*

Prairies and we have applied this to improved prediction. We have left a legacy of comprehensive datasets, improved observational and modelling techniques, a new generation of drought scientists, and a public better educated about drought. We have, in partnership with others in Canada and internationally, developed a plan to improve drought and water cycle prediction at multiple scales."

As one means of ensuring that these statements are realized, after each annual workshop, we issue a brief update statement. As of January 2008, DRI's status is:

"*We have continued to add datasets to characterize drought and to investigate the many factors leading to, sustaining and ending drought. We have developed interactions with other groups examining drought and other extremes in the United States and elsewhere. Our partners have organized an advisory group to ensure that there are strong two-way interactions with researchers. We are organizing our synthesis article on drought characterization and we have developed a strategy to assess and to contribute to improved predictive capabilities*."

The next two years of DRI will bring our effort together through collective efforts that directly address our objectives. This period is also being used to establish a DRI Follow-On. Given its progress, DRI is uniquely positioned to address drought anywhere in Canada and indeed it is well-positioned to examine hydrometeorological extremes anywhere in Canada.

In summary, a comprehensive study of drought over the Canadian Prairies is underway. This has brought together researchers from several disciplines and it is working with partners affected by drought. DRI is making a difference.

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User Expectations for the Drought Research Initiative (DRI)

by Rick Lawford[1], Harvey Hill[2], Elaine Wheaton[3], Irene Hanuta[4], Alf Warkentin[5] and Bill Girling[6]

1. Introduction

Drought is a major natural hazard that primarily affects western Canada, but other areas of Canada also are vulnerable. Drought impacts are complex due to their dependence on the timing, geographical extent, severity, and duration of a drought. For example, the agriculture industry is very sensitive to precipitation and temperature patterns associated with a drought during the growing season. The snowpack and the spring precipitation can also be important since the soil moisture reserves supply moisture needed by plants. Hydrological droughts are often initiated by a lack of winter precipitation, especially for watersheds with their headwaters in mountainous areas. However, spring and summer precipitation determines if the hydrologic drought becomes more severe or diminishes. Additional complexities in drought assessments occur when water use patterns are considered.

In order to facilitate the research community interactions with the user community there must be a shared understanding of the definition of drought. For this reason drought is sometimes classified as agricultural, hydrological, or socioeconomic, or, for some events, all of the above (Maybank et al., 1995). A definition that is often used considers drought as "a deficiency of precipitation from expected or "normal" that, when extended over a season or longer, results in insufficient water to meet the demands by agriculture, other sectors and the environment." This definition, while useful in many ways, does not account for factors such as wind, temperature, cloudiness, actual evaporation, soil moisture and reservoir and groundwater storage, all factors that affect drought impacts on human activities.

The onset and extent of droughts are not fully appreciated due to their slow, insidious development. However, as shown in Table 1, droughts were responsible for seven out of the ten most costly natural hazards according to an analysis of natural hazards in Canada by Etkin et al (2005) (see Table 1).

Based on the significance of drought and the extensive impacts of the 1999-2005 drought, the concept of a Canadian Drought Research Initiative (DRI) emerged. DRI was founded on two objectives, namely: (1) to better understand the physical characteristics of and the processes influencing Canadian Prairie droughts, and (2) to contribute to the better prediction of droughts. The objectives, themes, science questions and structure of DRI are elaborated in Stewart et al. (2008). While three DRI themes dealing with research to characterize drought, to understand drought processes and to predict drought, were approved for funding by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), the joint application projects with the user community did not garner financial support. In spite of the lack of resources, DRI scientists have been successful in developing a dialogue with the user community. This paper summarizes some highlights from these discussions.

Table 1. Largest Hazards in Canada (by damage / loss) (From Etkin et al., 2004)

Disaster	Year(s)	Location	Cost[1]
Drought	1980	Prairies	5.8
Freezing Rain	1998	Ontario to New Brunswick	5.4
Drought	2001/2002+	National	5.0
Drought	1988	Prairies	4.1
Drought	1979	Prairies	3.4
Drought	1984	Prairies	1.9
Flood	1996	Saguenay, QC	1.7
Flood	1950	Winnipeg, MA	1.1
Drought	1931-38	Prairies	1.0
Drought	1989	Prairies	1.0
Hailstorm	1991	Calgary, AB	< 1.0

[1] Cost is expressed in Billons 1999$.

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[3] Saskatchewan Research Council, Saskatoon

[4] Prairie Farm Rehabilitation Administration, Winnipeg

[5] Manitoba Water Stewardship, Winnipeg

[6] Manitoba Hydro, Winnipeg

2. Impacts of and lessons from the 1999-2005 drought
Unlike many previous droughts when only one or two economic sectors experienced impacts, the 1999-2005 drought affected agriculture, recreation, tourism, health, hydro-electricity production, and forestry. According to a preliminary analysis of the 2001 and 2002 drought years over Canada (Wheaton et al., 2005; Wheaton et al., 2008) the Gross Domestic Product was reduced by about $5.8 billion for 2001 and 2002. Other impacts included:

■ Employment losses that exceeded 41,000 jobs during the two-year period.

■ 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 an estimated $3.6 billion in 2001/2002. Farm input suppliers were hit by lower demand for their products, while food processors experienced shortages of raw material.

■ Previously reliable water supplies such as streams, wetlands, dugouts, reservoirs, and groundwater were placed under stress and often failed.

■ In British Columbia and Manitoba, hydroelectric generation was severely impacted, necessitating the operaton of backup thermal resources and purchases of power from neighbouring jurisdictions.

■ In 2002, the incidence of forest fires in Alberta increased to five times the ten-year average.

■ At least 32 incidents of massive dust storms with associated traffic accidents including several fatalities were reported in Saskatchewan between April and September 2001.

3. User needs and the application of DRI information
There is a clear need to augment our understanding of drought events and to make this information available to those who can plan effective responses to drought. DRI has promoted user involvement and interaction with its science team at each of its three annual workshops. From these interactions and deliberations of the recently formed DRI Partners Advisory Committee (PAC) a profile of user requirements for drought information has been developed. The key requirements are summarized under four general need statements.

Need #1: Users need to know when they are in drought conditions.

Drought impacts are often non-structural but can affect areas of thousands of square kilometres. Knowing when a region is in a drought is fundamental for planning and implementing adaptation measures and compensation programs. To provide more effective assessments of a drought it is essential to know an area's sensitivity to dry conditions throughout the annual cycle. As noted earlier, different sectors have different seasonal requirements for water and for drought information. Analysts must balance the concerns and drought criteria from different sectors as they provide their recommendations to senior government officials. As a result they need a better understanding of the adequacy of various indices in different regions and seasons.

The Government of Canada's Drought Watch, the North American Drought Monitor and the Prairie Farm Rehabilitation Administration's (PFRA) National Agroclimate Information Service are examples of monitoring programs that can provide a basis for informed decisions. However, users report that the coarse time and space resolution of the drought monitor limits its utility for some local applications. Even widely used drought indices require further assessment. For example, the Palmer Drought Index which is used extensively in temperate environments may not work as well at more northern latitudes or in the cold season. Other indices, such as the Standardized Precipitation Index, may need improvement for more arid regions.

At the provincial level, the drought monitoring task is made easier when a province has a drought plan in place that contains thresholds for identifying the onset of drought. Some provinces, such as Alberta, British Columbia and Ontario, have objective criteria for specifying drought conditions, although these criteria may not account for all of the complexities of drought processes. Developing these criteria is a challenge because of a lack of funds for research and monitoring and some inertia in agreeing to adopt a single unified objective strategy of using drought criteria for programmatic decisions.

To meet the specific needs of individual provinces, each prairie province has taken steps to augment the services available from the federal government. For example, Alberta Agriculture maintains an operational modeling effort to estimate drought conditions which quantifies soil moisture in time and space. The Alberta program provides good quality-monitoring information and advisory services, although concerns exist about the representativeness of certain indices and the consequences of using a variety of interpolation schemes in cases where spatial variability is large. In addition, there are limitations in the availability of accurate comprehensive data related to evapotranspiration, soil moisture and precipitation, which all are needed to drive and/or validate their drought monitoring models. Wintertime information, including snow pack and snow melt information also have been identified as important for monitoring soil moisture and ground water recharge. Other provinces approach drought monitoring and response in support of the agricultural sector differently, but have similar information requirements. For example, the Canadian Wheat Board has played a lead role in working with the provinces to develop a real-time meso-scale network in western Canada.

Information needed to support real-time water resource management decisions at the provincial or utility level relies largely on a knowledge of the surface and subsurface water stores as well as streamflow and soil moisture conditions. Many of the surface hydrology variables necessary to support agriculture are also needed for monitoring water availability and hence the collection and use of information needs to be closely coordinated across sectors. For example, coordination of networks in Manitoba involves Manitoba Water Stewardship, Environment Canada, Manitoba Agriculture, Manitoba Hydro and other Manitoba partner agencies working together to operate and improve climatic, hydrometric and soil moisture networks for use in monitoring and forecasting provincial water supplies.

DRI contributes to these efforts through its assessment of various drought indices and its research on the characterization of drought. Several projects use provincial data sets, thus allowing DRI to assist in clarifying the potential uses, benefits and limitations of these regional data systems and their derived products.

Need #2: Users need reliable forecasts of precipitation and other critical variables that relate to the initiation, intensification, continuation and termination of droughts.

Both the agriculture community and the water resources community need forecasts indicating when droughts will begin and end. For example, during periods of extended system-wide drought, Manitoba Hydro's hydropower generation may be severely impacted. Consequently, reliable forecasts of both the onset and termination of major system-wide drought events are critical for Manitoba Hydro to ensure that the operation of its integrated system is optimized. Seasonal forecast skill is limited by the inherent variability of Canada's climate and by the challenges faced by dynamic prediction models when they are used for seasonal forecasting. Some opportunities to develop prediction skill may be inferred by studies of teleconnection patterns such as the work done by Shabbar (1997) and others. DRI studies related to atmospheric circulation patterns during drought periods are described by Bonsal (2008) in this issue.

At the provincial level the needs for forecast variables are linked to the criteria used to monitor droughts. For example, provinces that rely on soil moisture to monitor drought would like accurate soil moisture forecasts to assess possible future drought conditions as well as improved in-season forecasts of factors such as precipitation and evaporation that drive changes in soil moisture. Increasingly, seasonal forecast groups are beginning to advocate the use of ensemble forecasts, although some users have questioned the utility of such forecasts. The hesitancy by some to use ensemble forecasts seems to stem from a lack of information and confidence about the type and accuracy of information they provide and how these forecasts can be applied to their particular needs.

Forecasts are necessary to guide decisions on how to operate dams and address issues of water availability for downstream uses. A number of provincial water management agencies issue outlooks that review the potential and implications for droughts as well as reservoir water supply projections and river flow and level forecasts during times of drought. Forecasts are often prepared based on statistically derived information on future weather conditions. There is a concern that such statistics may not be representative for some climatological situations and should be modified for an El Niño condition or for the onset of a drought. To meet these needs DRI is exploring the effects of sea surface temperature and soil moisture assimilation on seasonal drought prediction. DRI also is exploring the various tools (e.g. satellite data products, forecast evaluation procedures) that might be useful in assessing seasonal climate prediction products for western Canada. These activities are described in more detail in Stewart et al. (2008) and by reports and presentations available through the DRI website: www.drinetwork.ca.

Need #3: Users need to know the probability of drought events based on an understanding of physical processes

For planning purposes it is important to know the recurrence interval of major drought events. Water managers responsible for dam and reservoir construction need access to studies similar to those done by DRI for other historical droughts that have affected regional water supplies and hydropower production. Many planners use a single year or multiple years from the dustbowl of the 1930s as the benchmark worst event against which they evaluate their plans. For example, Manitoba Hydro uses a year in the 1930s decade as the "drought of record" to plan the system so that sufficient future resources are developed, ensuring they can supply the firm demand even under the expected worst drought conditions. However, the 1930s are difficult to address with detailed physical studies and comprehensive documentation because the data networks were much less developed than they are today and the number of reanalysis and model simulations available for the 1930s are limited. Manitoba Hydro is also assessing paleoclimate records (e.g. tree rings, lake sediments) within their watershed as another source of information to understand more about extreme droughts and climate variability in past climates (see Sauchyn et al., 2002). Manitoba Hydro would benefit from a long-term broad scale analysis of drought response using threshold criteria that are compatible with their operations to see how climate variability affects "hydroelectric" droughts over their region.

Many users are concerned about potential increases in the frequency and intensity of droughts in the future. Some climate models indicate that the frequency of extreme events such as floods and droughts will increase with increasing concentrations of atmospheric carbon dioxide. Estimations of the probability of multi-year droughts are particularly needed as these events have some of the largest negative impacts. This is very important for provincial water managers who need to plan and allocate water in a sustainable fashion in order to minimize the risk of water shortages for towns, industries, irrigation and individuals. Many believe that uncertainties associated with the implications of long-term climate change for drought remain sufficiently large that the best course of action lies in preparing for potentially increasing climate variability. For example, PFRA is working on a planned approach for agriculture to develop tools and policies to reduce drought impacts; to support and develop current activities that work, and to develop and implement new activities to adapt to drought. It is recognized that federal activities would be most effective if they are linked to the provinces by sustained institutional partnerships. It also is important to ensure that the key factors associated with these potential changes in the characteristics of drought are carefully monitored so any shifts in climate can be detected and users can receive early notification of such changes.

In some ways the DRI multi-year drought seemed to be unique in that it persisted through a number of different sea-surface temperature and teleconnection patterns: some of which have occurred on other occasions without producing such significant droughts. While DRI has not been funded to look at comparisons of the 1999-2005 drought with other droughts, some work is being carried out (Bonsal, 2008). An understanding of the processes that cause the droughts based on DRI analysis could enable more insightful assessments of extremes in future studies because it will provide a stronger basis for exploring the frequency of the causative factors that lead to drought than a purely statistical analysis of historical and projected values of temperature and precipitation.

Need #4: Users need guidance on how to use physical understanding and insights to reduce vulnerability to drought and mitigate drought impacts.

There are needs for inputs to policy and programmatic responses to drought at all levels of government including the municipal level. For the agricultural sector, Canada needs to take a proactive stance on agricultural drought to ensure it maintains its competitive advantage in world food markets through its natural climate advantage and its historic government support to this sector. This competitive advantage can be best achieved by long-term research, investments, and policies. Historically, governments have responded to agricultural droughts by supporting a range of on-farm actions such as water supply development, water conservation, feed support for livestock and education programs to name a few. While these programs are beneficial for individual farmers the benefits of a broader strategic approach for the sector should also be developed. To this end, federal-provincial committees are developing a framework for the next generation of agricultural policy framework, known as Growing Forward, as well as a national drought strategy for the medium- to long-term. Drought management and adaptation for longer-term climate change will continue to receive attention in federal-provincial discussions and the research work of DRI will have continued relevance to, and benefit for, understanding drought, contributing to policy and sustaining Canada's economic development.

The impacts of drought are often regional in nature. In order to target mitigation strategies that are most appropriate it is important to assess the area's vulnerability to drought. The risk associated with a drought is dependent on the threat of the event (representing the climate and any other factors that could affect the water supply) and the vulnerability to drought (representing the economic and engineered infrastructure in a region). As a first approximation areas which rely heavily on water would be more susceptible to drought although Venema (2007) has shown that vulnerability and resilience contain a strong learning component because many farmers in drought-prone areas have learned to cope with drought better than those in areas where drought occurs irregularly.

For historical and jurisdictional reasons, drought management plans are frequently developed for provinces but they can be made even more specific for a region or a city. While governments can put in place an economic safety net, the decisions about drought response often are most effective when they are agreed to by those who will be implementing the plans.

During droughts, many provinces activate provincial inter-departmental drought committees which coordinate provincial responses to droughts. They also develop newsletters and other communication tools in order to provide information on the drought and options for water conservation. Most provinces rely on federal information systems as well as data from their own networks, such as provincial groundwater observation networks, to support their decisions regarding drought response. These committees encourage drought responses tailored to provincial needs. For example, the Manitoba Water Services Board helps farmers acquire the necessary water supplies, such as pumps, when a drought is developing,

The development of a risk-based approach to drought management can integrate management considerations on all scales. These approaches should include internal risk assessment and sensitivity analyses of more severe droughts (Botterill and Fisher, 2003; NDPC, 2000). As described by Wilhite et al. (2005), countries such as South Africa, Australia and the United States are developing these approaches for drought management. Risk assessment should be supported by reliable drought prediction capabilities and monitoring systems. However, these approaches must ensure that the needs and concerns of all levels of government are addressed. DRI can provide research support at each of these jurisdictional levels. For example, DRI hydrological process research on sublimation and blowing snow can provide practical advice on stubble management for optimizing snowpack retention through the winter months. On the larger scale, innovations developed through DRI for using satellite and in-situ data should assist in developing a stronger scientific basis for risk-based approaches.

4. The Role of the Partners Advisory Committee

The DRI Network seeks to connect its research to practical applications wherever appropriate. Three opportunity areas of focus have been identified: data products, analytical tools and models; improved forecasts, and syntheses that can be used for policy development. In order to help focus the applications aspects of DRI, a small advisory committee made up of some of the DRI Partners has been established to provide advice to the DRI Board of Directors (BoD). With this level of reporting it is believed that the advice will influence DRI research at its most fundamental levels.

The Terms of reference for this committee are as follows:

1) To provide advice and assessments to the BoD on the status of DRI interactions with stakeholders;

2) To identify linkages and propose working groups and recommend actions that could be taken to develop specific proposals; and

3) To develop an outreach strategy to ensure DRI results are used effectively.

Membership on the committee includes representatives from federal agencies and from water management and agricultural agencies in western Canadian provinces. One potential area of activity involves preparing for droughts using scenarios and simulation exercises. The purpose of these activities is to identify gaps in current capacity to respond to drought and to better understand potential challenges arising from demographic and economic trends. PFRA's Climate Decisions Support and Adaptation Unit is working with DRI to explore how to develop prototypes related to this activity.

5. Summary and Next Steps

This review of the user needs has identified a number of areas where more research is needed. In particular, users need to know:

1) information for determining when a region is in drought conditions,

2) reliable forecasts of drought and associated climate variables such as precipitation and other drought variables.

3) the probability of causative factors for droughts of different temporal or spatial extent.

4) ways to apply drought research results to reducing vulnerability to drought and to mitigating its impacts.

DRI has made significant progress in addressing the first two needs and has made some contributions to the third and fourth issues. DRI is seeking opportunities for a follow-on study that will provide opportunities for addressing droughts and other extremes in both past and future climates in a national and, possibly, an international context. In terms of the societal impacts of drought, questions such as: "how are organizations affected by drought?", "what is the nature of these impacts?", and "how can drought impacts be alleviated?" could be addressed. DRI is committed to continuing its dialogue with users to obtain inputs and advice as it develops its second phase proposal.

6. Acknowledgements:

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Appendix A

Members of the DRI Partner Advisory Committee

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Description de la page couverture

Ce numéro: Les sécheresses prolongées sur grande superficie sont parmi les catastrophes naturelles les plus coûteuses au Canada. Elles ont des répercussions profondes sur tout un éventail de secteurs, notamment sur l'agriculture, les forêts, l'industrie, les municipalités, les loisirs, la santé, la société et les écosystèmes aquatiques. Bien que la plupart des régions du Canada doivent faire face à la sécheresse, les Prairies canadiennes sont les plus vulnérables avec au moins 40 sécheresses qui sont survenues depuis deux siècles. Mais rarement cette sécheresse a-t-elle suscité autant d'inquiétudes que lors de l'épisode 1999-2005 qui a abouti à la pire sécheresse qui soit survenue au Canada depuis un siècle, touchant plus particulièrement les Prairies canadiennes. Pour traiter de telles sécheresses extrêmes, un réseau de recherche du nom de DRI (**D**rought **R**esearch **I**nitiative – Initiative de recherche sur la sécheresse) a été formé. Le centre d'intérêt du réseau DRI consiste à mieux comprendre la façon dont les sécheresses surviennent, évoluent et prennent fin afin de comprendre leur structure interne et de contribuer à une meilleure prédiction de tels événements. Afin de réaliser cet objectif, on considère la sécheresse sous différents points de vue en tenant compte de l'atmosphère, du sol incluant les processus de la végétation et du sous-sol. De plus, la communauté de recherche du réseau DRI travaille étroitement avec plusieurs partenaires concernés par la sécheresse et qui ont tous intérêt à faire face à de tels événements dans le futur.

Trois articles présentés dans ce numéro traitent des sécheresses au Canada tout en favorisant la continuité des objectifs de l'équipe du réseau DRI. Ces articles donnent une vue d'ensemble sur les sécheresses au Canada et met l'accent sur celles des Prairies canadiennes (**page 79**). De plus, une description des aspects du réseau DRI suit (**page 87**). En conclusion, on évalue les attentes des utilisateurs de la communauté du réseau DRI, incluant leurs besoins particuliers (**page 97**).

Page Couverture: La photo en page couverture a été prise près de Consul, Saskatchewan, en avril 2002. Elle a été prise par Ted Banks, Agriculture et Agroalimentaire Canada.

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Improved seawater thermodynamics: How should the proposed change in salinity be implemented?

by SCOR/IAPSO Working Group 127

February 2008

Background

The SCOR/IAPSO Working Group 127 on the "Equation of State and Thermodynamics of Seawater" is charged with providing improved algorithms and descriptions of the thermodynamic properties of seawater. The working group has made significant progress on many of its goals, and it is now time to seek the advice of the oceanographic community regarding the best practical ways of adopting these developments into oceanographic practice. The Working Group has met twice to date, once in Warnemünde in 2006, then in Reggio Calabria in 2007. Our next meeting is in Berlin in September 2008.

The working group will soon provide the most accurate algorithms to date for the thermodynamic properties of seawater (such as density, entropy, enthalpy, specific heat capacity, etc). In order to achieve such accuracy it became evident that a salinity variable is required that more accurately represents absolute salinity than does the conductivity-based Practical Salinity. Spatial variations in the composition of seawater upsets the relationship between Practical Salinity S (which is a function of conductivity, temperature and pressure) and Absolute Salinity S_A (defined as the mass of dissolved material per mass of seawater solution). If the thermodynamic properties of seawater are to be written in terms of just one type of salinity, then they are much closer to being functions of (S_A, t, p) than being functions of (S, t, p). Moreover, Absolute Salinity is a conservative property (that is conserved when turbulent mixing occurs) whereas Practical Salinity is not conservative.

Absolute salinity for seawater of Reference Composition

In order to progress toward evaluating Absolute Salinity our first task was to define the relative concentrations of the constituents of Standard Seawater. This we have done, and this work is published in Millero et al (2008a). The abstract of this paper is as follows.

Fundamental determinations of the physical properties of seawater have previously been made for Atlantic surface waters, referred to as "Standard Seawater". In this paper a Reference Composition consisting of the major components of Atlantic surface seawater is determined using these earlier analytical measurements. The stoichiometry of sea salt introduced here is thus based on the most accurate prior determination of the composition, adjusted to achieve charge balance and making use of the 2005 atomic weights. Reference Seawater is defined as any seawater that has the Reference Composition and a new Reference-Composition Salinity S_R is defined to provide the best available estimate of the Absolute Salinity of both Reference Seawater and the Standard Seawater that was used in the measurements of the physical properties. From a practical point of view, the value of S_R can be related to the Practical Salinity S by

$$S_R = (35.165\,04 / 35) \text{ g kg}^{-1} \times S.$$

Reference Seawater that has been normalized to a Practical Salinity of 35 has a Reference-Composition Salinity of exactly S_R = 35.165 04 g kg^{-1}.

The new independent salinity variable S_R is intended to be used as the concentration variable for future thermodynamic functions of seawater, as an SI-based extension of Practical Salinity, as a reference for natural seawater composition anomalies, as the currently best estimate for Absolute Salinity of IAPSO Standard Seawater, and as a theoretical model for the electrolyte mixture "seawater".

As described in this abstract, *for seawater of standard composition* we have been able to relate the Absolute Salinity to the Practical Salinity; for example, at a Practical Salinity of 35, seawater of Reference Composition has an Absolute Salinity of 35.165 04 g kg^{-1}. We expect shortly to be able to recommend an algorithm that accounts for the variation of seawater composition from the standard composition. That is, we soon expect to be able to recommend an algorithm $S_A = S_A(S_R, , , ,)$ where the extra arguments will be either measured parameters (such as total alkalinity, silicate and nitrate) or more simply the spatial locations longitude, latitude and pressure. Millero and Kremling (1976), Millero (2000) and Millero et al (2008b) are precursor papers to such an algorithm.

Advantages of Absolute Salinity over Practical Salinity

Absolute Salinity has the following advantages over Practical Salinity for oceanographic use.

1. The definition of Practical Salinity S on the PSS-78 scale is separate from the system of SI units. Absolute Salinity can be expressed in the unit (g kg^{-1}). Adopting this SI unit for salinity would terminate the ongoing controversies in the oceanographic literature about the use of "psu" or "pss" and make research papers more readable to the outside scientific community and consistent with SI.

2. The freshwater mass fraction of seawater is not (1 – 0.001 S). Rather, it is (1– 0.001 S_A /(g kg ^{1})), where S_A is the Absolute Salinity, defined as the mass fraction of dissolved material in seawater. The values of S_A /(g kg^{-1}) and S are known to differ by about 0.5%. There seems to be no good reason for continuing to ignore this known difference, e.g., in ocean models.

3. PSS-78 is limited to the salinity range 2 to 42. For a smooth crossover on one side to pure water, and on the other side to concentrated brines up to saturation, as e.g. encountered in sea ice at very low temperatures, salinities beyond these limits need to be defined. While this poses a challenge for S, it is not an issue for S_A.

4. The theoretical Debye-Hückel limiting laws of seawater behaviour at low salinities, used for example in the determination of the Gibbs function of seawater, can only be computed from a chemical composition model, which is available for S_R but not for S.

5. For artificial seawater of Reference Composition, S_R has a fixed relation to Chlorinity, independent of conductivity, salinity, temperature, or pressure.

6. The next largest improvement in the equation of state of seawater will come from incorporating variations in the composition of seawater, that is, from calling the equation of state with Absolute Salinity rather than with Reference Salinity. The determination of Absolute Salinity is facilitated by the introduction of the Reference Composition and Reference Salinity.

7. Absolute Salinity S_A is a conservative variable, whereas, in the presence of compositional variations, Practical Salinity S (which is essentially determined by conductivity alone) is not a conservative variable. All of our oceanographic practice assumes that "salinity" is a conservative variable (e.g. ocean model codes, the practice of mixing along straight lines on salinity-potential temperature diagrams, inverse modelling etc).

Expanding on point 7 above, it seems clear that we presently use Practical Salinity S as though it is a conservative variable, and yet we now know that it is not; for a given Absolute Salinity, Practical Salinity varies by up to 0.02 between different major ocean basins (Millero, 2000). This non-conservative regional variation in Practical Salinity is at least seven times the error with which salinity can be measured by modern instrumentation at sea. This difference of 0.02 in Practical Salinity causes differences in density that are also several times greater than the remaining uncertainty in the best algorithms for the density of seawater. It seems that in our oceanographic practice we intuitively ascribe the conservative properties of Absolute Salinity to our "salinity" variable, which to date has been Practical Salinity. For example, if we were intent on interpreting the salinity of an ocean model as Practical Salinity, then the salt conservation equation should contain a non-conservative source term to take account of the spatial variations in the composition of seawater.

Here we summarize the reasons why Absolute Salinity is the preferred salinity variable for oceanographic research.

■ It will be preferred by journals since it is an SI unit.

■ It is the natural salinity variable for ocean models since they assume that their salinity variable is conservative, hence it should be used to initialize ocean models at all depths.

■ It is the natural variable to use in inverse models, budget studies and on salinity-temperature diagrams because its conservative nature justifies turbulent mixing occurring along straight lines on such a diagram.

■ The freshwater fraction and the meridional freshwater flux follow naturally when using Absolute Salinity but not when using Practical Salinity.

■ By using Absolute Salinity in the algorithm for the equation of state, the effects of the spatial variations of seawater composition are accounted for, while if Practical Salinity is used in such a call to the equation of state, a density error is incurred.

■ It is the common salinity variable used in engineering, natural and geosciences outside oceanography, where Practical Salinity is often unknown or misconstrued.

■ It is applicable to low concentrations in brackish lagoons and river mouths, to high concentrations in freezing or desiccating brines, as well as at higher temperatures in desalination plants, whereas Practical Salinity is defined only in the range $2<S<42$.

■ If necessary for chemical or biological reasons, all partial ion concentrations in a sample are easily available, to which Practical Salinity is unrelated.

The SCOR/IAPSO Working Group 127 regards these as compelling reasons for adopting Absolute Salinity as the new preferred salinity variable in the analysis of oceanographic data. Accordingly we are formulating new algorithms for density, enthalpy, entropy, potential temperature, sound speed, etc in terms of Absolute Salinity, temperature and pressure (Feistel (2008)). The extended validity range of the new formulas in temperature and salinity precludes using Practical Salinity as the independent variable of these thermodynamic quantities. For example, in situ density will have the functional form ρ (S_A, t, p) and potential temperature will have the functional form θ (S_A, t, p, p_r). Absolute Salinity S_A will be defined as

$$S_A = S_R + \delta S_A$$

where Reference salinity S_R is simply proportional to Practical Salinity S as described in Millero et al (2008), namely by

$$S_R = (35.165\ 04 / 35)\ \text{g kg}^{-1} \times S\ ,$$

and δS_A is the difference between Absolute and Reference Salinities. δS_A will be available as a look up table as a function of latitude, longitude and pressure and also as an alternative linear relationship of nutrient and silicate concentrations, or for example, as a Calcium excess estimate from the river discharge into estuaries. We expect to have algorithms available before the end of 2008.

How to adopt Absolute Salinity?

Having made the case that Absolute Salinity possesses many advantages over Practical Salinity, how should present oceanographic practice adapt to incorporate these advantages?

The obvious thing to do would be to decide on a date on which the whole community ceases to use Practical Salinity and switches to using Absolute Salinity. However the algorithm to convert Reference Salinity to Absolute Salinity is less mature and will probably remain a "work in progress" for several years. Moreover, data that are stored in archives should have a very close connection to a measurement (like temperature or conductivity) rather than being the result of an algorithm that is likely to change with time. Hence one cannot really imagine storing Absolute Salinity in data bases. Rather, the closest thing to do in this vein is to store Reference Salinity.

Storing Reference Salinity in data centres would have the advantage that it is an SI unit. However before the equation of state (or other thermodynamic quantities) can be evaluated using the new software, the Reference Salinity data needs to be converted to Absolute Salinity using the most up-to-date version of this software. Moreover, the community cannot completely abandon Practical Salinity since it will remain as the salinity variable in the archives for cruises undertaken before the change-over date. By changing the salinity variable that is reported from cruises to data bases from Practical Salinity to Reference Salinity the possibility of contamination of the data archives arises as salinity of one type is incorrectly labelled and stored as the other type of salinity.

In the long run, as with many other historical non-SI units like torr, cal or dyn, it would seem to be an advantage to use only Reference Salinity and abandon the use of Practical Salinity completely. If Reference Salinity were the salinity variable to be used in all of the revised thermodynamic algorithms, the argument for "biting the bullet" and abandoning Practical Salinity as much as possible would seem to be the correct path. But it is Absolute Salinity that we seek, and Reference Salinity is only part way towards the evaluation of Absolute Salinity. Given this, is it worthwhile changing the present archiving practice in favour of a variable (Reference Salinity) that is still not the final salinity that we will use (Absolute Salinity)?

Any choice of action inherently involves compromises, and the best course of action is not obvious to the Working Group. As a way of focussing the discussion we outline two possible routes for adopting the advantages of Absolute Salinity, labelled Option 1 and Option 2.

Option 1

■ Change from reporting Practical Salinity to reporting Reference Salinity to national and international data bases. This implies that the data bases store Practical Salinity from the old cruises and store Reference Salinity from new cruises (from say 1st January 2010).

■ Provide software [for example, of the form $S_A(S_R, x, y, p)$] to produce the best available estimate of Absolute Salinity from Reference Salinity (using additional information on position or water properties).

■ Have all the thermodynamic software in the form $\rho\,(S_A, t, p)$.

Discussion of Option 1

The main advantage of Option 1 is that the community eventually ceases to use the non-SI unit Practical Salinity, and instead uses the two SI salinity measures, Reference Salinity and Absolute Salinity.

A drawback of Option 1 is that there will be cases of contamination of the data bases where cruise salinity is labelled and stored as Reference salinity whereas in fact it is Practical Salinity data, and vice versa. This kind of error presently contaminates the temperature, oxygen and pressure/depth data bases.

Since both S and S_R are simply measures of conductivity, and since they are simply proportional to each other, will it be seen that we are taking a course of action that has potential for confusion for only academic benefit?

Recall that scientific work and papers are mostly done with potential temperature θ rather than in situ temperature t so the first thing that one usually does with the S, t, p data from a data centre is to form θ. Similarly, scientific work and papers should be done with Absolute Salinity rather than Reference Salinity so the first thing that one needs to do under Option 1 with the ,S_R t, p data from a cruise or from a data centre is to form not only θ but also S_A. This analogy with what we already do with storing the measured variable t but using the derived variable θ is very close.

Under Option 1 we cannot imagine that the community can altogether forget about Practical Salinity however, as the data from older cruises (e.g. all of WOCE) are stored in data centres in terms of Practical Salinity. These data will need converting first to Reference Salinity and then to Absolute

Salinity before the thermodynamic routines such as potential temperature, density, potential enthalpy etc, can be called by oceanographic researchers.

There will be some instances when the new software is called with the salinity data being *S* and in those instances an error will be made. This type of error is an undesirable consequence of both Options 1 and 2.

Option 1 requires manufacturers (such as Seabird) to change what they presently do. The instruments will need to output their salinity in terms of Reference Salinity. Also the ampoules of standard seawater will need to quote their salinity in terms of Reference Salinity. The transition date of say 1st January 2010 has to be handled very carefully in these respects. Further, anyone wanting to make use of older ampoules will have to be aware of the transition and how to deal with it.

Option 2

■ Continue to report Practical Salinity *S* from cruises and to have only Practical Salinity *S* stored at national and international data centres.

■ Provide software [for example, of the form $S_A(S, x, y, p)$] to produce the best available estimate of Absolute Salinity from Practical Salinity (using additional information on position or water properties.

Have all the thermodynamic software in the form $\rho(S_A, t, p)$.

Discussion of Option 2

By reporting only *S* in data bases we would expect to greatly reduce the possibility of salinity data being mislabeled in data bases.

Since both *S* and S_R are simply measures of conductivity, option 2 is consistent with the argument that there is little value in replacing one measure of conductivity (namely Practical Salinity) with another (namely Reference Salinity) in data bases. Rather, under Option 2 data centres store *S* and *S* alone.

As mentioned above, scientific work and papers are mostly done with potential temperature θ rather than in situ temperature *t* so the first thing that one usually does with the *S, t, p* data from a data centre is to form θ . Similarly, scientific work and papers will be mostly done with Absolute Salinity rather than Practical Salinity so the first thing that one needs to do under Option 2 with the *S, t, p* data from a cruise or from a data centre is to form not only θ but also S_A . This analogy with what we already do with storing the measured variable *t* but using the derived variable θ suggests that storing *S* but using S_A will not cause oceanographers any serious difficulties.

There will be some instances when the new software is called with the salinity data being *S* and in those instances an error will be made. This type of error is an undesirable consequence of both Options 1 and 2. However this error will affect the results and the publications arising out of those who make this error, but this error will not contaminate an archived data set.

Option 2 does not require manufacturers (such a Seabird and the Standard Seawater Service) to change what they presently do. Rather, Option 2 puts the responsibility for the changes in the hands of practicing research oceanographers.

Request for your input

The above two options are just two of many options; please do not feel constrained in your comments to these options. We seek input from the oceanographic community on how to gain the advantages of adopting Absolute Salinity in our oceanographic research work. The key issue seems to revolve around which type of salinity is required to be reported to and archived by oceanographic data centres. We encourage frank responses. Each response will be thoughtfully considered by the Working Group. Please email your comments to trevor.mcdougall@csiro.au with the words “Comment for WG127 on how to adopt Absolute Salinity” as the message title.

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A-O Abstracts Preview

Avant Première des résumés de A-O

The following abstracts will soon be published in your ATMOSPHERE-OCEAN publication.

Les résumés suivants paraîtront sous peu dans votre revue ATMOSPHERE-OCEAN.

Glacial Ocean Circulation and Property Changes in the North Pacific

SEONG-JOONG and YOUNG-GYU PARK

Abstract
The glacial properties and circulation changes in the North Pacific Ocean are investigated using a coupled ocean-atmosphere-sea-ice climate model. With glacial boundary conditions, an increase in potential density in the upper layers of the northern North Pacific makes the water column highly unstable and eventually results in the enhancement of North Pacific Intermediate Water (NPIW) production, consistent with proxy evidence. The NPIW outflow reaches deeper layers than in the present ocean, but remains largely confined to the North Pacific. The increase in potential density is predominantly caused by the increase in salinity and, to a lesser extent, by decreases in temperature. The increase in surface salinity is especially high in the Sea of Okhotsk and the western Bering Sea, which are possible source areas of glacial NPIW production. In these regions, an increase in brine release due to a marked increase in sea ice, evaporation exceeding precipitation, and a reduction in river discharge contribute to the increase in surface salinity. In short, reduction in freshwater input to the northern North Pacific is the main reason for the increase in the production and outflow of glacial NPIW.

Résumé
Nous étudions les changements dans les propriétés et la circulation glaciaire dans l'océan Pacifique Nord au moyen d'un modèle climatique couplé océan-atmosphère-glaces de mer. Avec des conditions glaciaires aux limites, une augmentation de la densité potentielle dans les couches supérieures du Pacifique Nord septentrional rend la colonne d'eau très instable et entraîne éventuellement une accélération de la production d'eaux intermédiaires du Pacifique Nord, qui s'accorde avec les preuves indirectes. La sortie d'eaux intermédiaires du Pacifique Nord atteint des couches plus profondes que dans l'océan actuel mais demeure largement confinée au Pacifique Nord. L'accroissement de densité potentielle est principalement causé par l'accroissement de la salinité et, dans une moindre mesure, par des diminutions de température. L'accroissement de la salinité en surface est particulièrement marqué dans la mer d'Okhotsk et dans l'ouest de la mer de Béring, qui sont des régions sources possibles de production d'eaux intermédiaires du Pacifique Nord glaciaires. Dans ces régions, une augmentation du rejet de saumure causé par une augmentation marquée des glaces de mer, l'excès de l'évaporation sur les précipitations et une réduction des débits fluviaux contribuent à l'accroissement de la salinité en surface. En résumé, la réduction de l'apport d'eau douce dans le Pacifique Nord septentrional est la principale raison de l'accroissement de la production et la sortie d'eaux intermédiaires du Pacifique Nord glaciaires.

Cloud type observations and trends in Canada 1953-2003

E. J. MILEWSKA

Abstract
The monitoring of cloud amount and type in Canada is discussed in detail, including observing, archiving, data transmission procedures and practices, and automation.

There have been some major monitoring challenges since 1953. In 1977, the network-wide replacement of detailed cloud layer amounts and obscuring phenomena by broad sky conditions, based on summation amounts, imposed analysis of frequency of occurrence of mainly cloudy conditions rather than actual amounts. Partial automation with Automated Weather Observing Systems resulted in the cessation of observations of higher clouds and cloud types, as well as the incompatibility of sky coverage with human observations at eight percent of stations.

For every hourly report from eighty-four airport stations, from 1953 to 2003, each layer is classified according to cloud type and related standard base height into three levels of clouds, low, middle and high clouds. Trends in occurrence of summation amounts of mainly cloudy conditions at each of these three levels are computed on annual, seasonal, daytime and nighttime scales, together with annual trends in occurrence of selected convective and stratiform clouds. Based on annual anomalies averaged over the country and provinces, no major network-wide systematic discontinuities were noted; on average, on an annual basis over the entire network, slight decreasing trends are noted for summation amounts of mainly cloudy conditions at low and middle levels, and increasing trends at high levels.

The increasing trend at high levels is indeed remarkable. The rate of increase, especially rapid until 1974, has been shown to be caused by a prominent increase in cirrus cloud reports. The link between this rise and the increase in air traffic was established by others in the United States. This

link may also apply in Canada, which experienced a similar expansion in aviation.

Notably, the largest increase in high nighttime cloudiness and decrease in low-middle cloudiness is evident in western Canada, possibly contributing to the recently observed warming of daily minimum and maximum temperatures there.

The occurrence of stratiform clouds at all levels exhibits significant decreasing trends across the country, except for southern Ontario. Clouds of intense convection show pronounced decreasing trends in western Canada, while not much change is evident elsewhere. Similar to cirrus, stratocumulus is notable as it shows strong positive trends everywhere in the country. On the other hand combined stratus and stratus fractus clouds exhibit decreasing trends except over British Columbia where the opposite occurs. The findings concerning stratocumulus, stratus and stratus fractus clouds in Canada are similar to the findings in the United States.

Résumé
Nous discutons en détail de la surveillance de l'étendue et du type des nuages au Canada, y compris l'observation, l'archivage, les procédures et pratiques de transmission des données et l'automatisation.

La surveillance a posé d'importants défis depuis 1953. En 1977, le remplacement à la grandeur du réseau des étendues détaillées des couches nuageuses et des phénomènes obscurcissants par des états du ciel généraux fondés sur les étendues cumulatives a imposé l'analyse de la fréquence des conditions principalement nuageuses plutôt que des étendues réelles. L'automatisation partielle au moyen de systèmes d'observation météorologique automatiques a entraîné la fin de l'observation du type de nuages et des nuages élevés de même qu'une incompatibilité de la couverture nuageuse avec les observations faites par des humains à huit pour cent des stations.

Pour chaque observation horaire à 84 stations d'aéroports, de 1953 à 2003, chaque couche est classée, selon le type de nuage et la hauteur de base normalisée correspondante, dans trois niveaux : nuages bas, moyens et élevés. Les tendances dans l'occurrence des étendues cumulatives des conditions principalement nuageuses à chacun de ces trois niveaux sont calculées aux échelles annuelle, saisonnière, diurne et nocturne en même temps que les tendances annuelles dans l'occurrence de nuages convectifs et stratiformes sélectionnés. D'après les anomalies annuelles moyennées pour le pays et les provinces, aucune discontinuité systématique importante dans l'ensemble du réseau n'a été trouvée; en moyenne, au cours d'une année dans l'ensemble du réseau, on observe de faibles tendances à la baisse pour les étendues cumulatives des conditions principalement nuageuses dans les niveaux bas et moyens et des tendances à la hausse dans les niveaux élevés.

La tendance à la hausse dans les niveaux élevés est en fait remarquable. Le taux d'accroissement, particulièrement rapide jusqu'en 1974, a été expliqué par un accroissement important des observations de cirrus. D'autres chercheurs aux États-Unis ont établi le lien entre cet accroissement et l'accroissement du trafic aérien. Ce lien peut aussi s'appliquer au Canada, où le secteur de l'aviation a connu une expansion semblable.

Détail d'intérêt, la plus forte augmentation de nuages élevés la nuit et diminution de nuages bas ou moyens se produit dans l'ouest du Canada, ce qui contribue peut-être à la hausse des températures journalières minimales et maximales récemment observée dans cette région.

L'occurrence de nuages stratiformes à tous les niveaux accuse une tendance à la baisse appréciable dans tout le pays sauf dans le sud de l'Ontario. Les nuages de convection intense affichent une tendance à la baisse prononcée dans l'ouest du Canada alors qu'on ne constate pas beaucoup de changement ailleurs. Comme pour le cirrus, le stratocumulus est remarquable par les fortes tendances positives qu'il affiche partout au pays. D'autre part, le stratus et le stratus fractus combinés affichent des tendances à la baisse sauf en Colombie-Britannique où l'inverse se produit. Les conclusions tirées à propos du stratocumulus, du stratus et du stratus fractus au Canada concordent avec les conclusions tirées aux États-Unis.

Sea level responses to climatic variability and change in Northern British Columbia

DILUMIE S. ABEYSIRIGUNAWARDENA and IAN J. WALKER

Abstract
Sea level responses to climatic variability (CV) and change (CC) signals at multiple temporal scales (inter-decadal to monthly) are statistically examined using long-term water level records from Prince Rupert (PR) on the north coast of British Columbia. Analysis of observed sea level data from PR, the longest available record in the region, indicates an annual average mean sea level (MSL) trend of +1.4±0.6 mm yr^{-1} for the period (1939-2003), as opposed to the longer term trend of 1±0.4 mm yr^{-1} (1909-2003). This suggests a possible acceleration in MSL trends during the latter half of the twentieth century. According to the results of this study, the causes behind this acceleration can be attributed not only to the effects of global warming but also to cyclic climate variability patterns such as the strong positive Pacific Decadal Oscillation (PDO) phase that has been in existence since mid-1970s. The linear regression model based on highest sea levels (MAXSL) of each calendar year showed a trend (3.4 mm yr^{-1}) exceeding twice that of MSL. Previous work shows that the influence of vertical crustal motion on relative sea level is negligible at PR.

Relations between sea levels and known CV indices (e.g., the Multivariate ENSO Index (MEI), PDO, Northern Oscillation Index (NOI), and Aleutian Low Pressure Index (ALPI)) are explored to identify potential controls of CV phenomena (e.g., the El Niño Southern Oscillation (ENSO) and PDO) on regional MSL and MAXSL. Linear and non-linear statistical methods including: correlation analyses, multiple regression, Cumulative Sum (CumSum) analysis, and Superposed Epoch Analysis (SEA) are used. Results suggest that ENSO forcing (as shown by the MEI and NOI indices) exerts significant influence on winter sea level fluctuations, while the PDO dominates summer sea level variability. The observational evidence at PR also shows that, during the period 1939-2003, these cyclic shorter temporal scale sea level fluctuations in response to CV were significantly greater than the longer term sea-level rise trend, by as much as an order of magnitude and with trends over twice that of MSL. Such extreme sea level fluctuations related to CV events should be the immediate priority for the development of coastal adaptation strategies, as they are superimposed on long term MSL trends, resulting in greater hazard than longer term MSL rise trends alone.

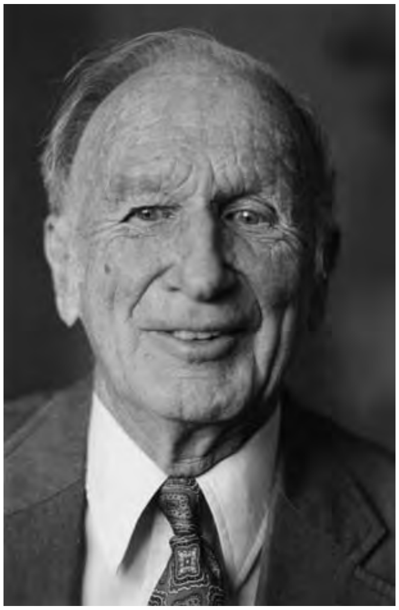
Résumé [traduit par la rédaction]
Nous examinons, du point de vue statistique, les réponses du niveau de la mer aux signaux de variabilité climatique (VC) et de changement climatique (CC) à des échelles temporelles multiples (d'interdécennale à mensuelle) à l'aide des enregistrements de niveaux d'eau à long terme de Prince Rupert (PR) sur la côte nord de la Colombie-Britannique. L'analyse des données d'observation du niveau de la mer de PR, la plus longue série d'enregistrements dans la région, indique une tendance annuelle moyenne du niveau moyen de la mer (NMM) de +1,4±0,6 mm an^{-1} pour la période (1939–2003) comparativement à la tendance à plus long terme de +1±0,4 mm an^{-1} (1909–2003). Cela suggère une possible accélération des tendances du NMM durant la deuxième moitié du XX^{e} siècle. Selon les résultats de cette étude, on peut attribuer les causes de cette accélération non seulement aux effets du réchauffement planétaire mais aussi à des configurations de variabilité climatique cycliques, comme la forte phase positive de l'oscillation décennale du Pacifique (ODP) qui perdure depuis le milieu des années 1970. Le modèle de régression linéaire basé sur les plus hauts niveaux de la mer (MAXSL) de chaque année civile a montré une tendance (3,4 mm an^{-1}) de plus du double de celle du NMM. Des travaux précédents montrent que l'effet des mouvements verticaux de la croûte terrestre sur le niveau relatif de la mer sont négligeables à PR.

Nous explorons les relations entre les niveaux de la mer et les indices VC connus — p. ex. l'indice ENSO multivarié (MEI), l'ODP, l'indice d'oscillation boréale (IOB) et l'indice de dépression des Aléoutiennes (ALPI) — pour identifier l'influence potentielle des phénomènes de VC — p. ex. le El Niño—oscillation australe (ENSO) et l'ODP — sur le NMM et le MAXSL régionaux. Nous utilisons des méthodes statistiques linéaires et non linéaires, notamment les analyses de corrélation, la régression multiple, l'analyse des sommes cumulées (CumSum) et l'analyse par époques superposées (SEA). Les résultats suggèrent que le forçage ENSO (comme le montrent les indices MEI et IOB) exercent une influence appréciable sur les fluctuations du niveau de la mer en hiver alors que l'ODP domine la variabilité du niveau de la mer en été. Les preuves observationnelles à PR montrent aussi que, durant la période 1939–2003, ces fluctuations cycliques du niveau de la mer de plus petite échelle temporelle en réponse aux phénomènes de VC étaient nettement plus importante que la tendance à la hausse du niveau de la mer à plus long terme, par jusqu'à un ordre de grandeur et avec des tendances plus de deux fois plus grandes que celle du NMM. Des fluctuations du niveau de la mer aussi extrêmes liées aux événements de VC devraient constituer la priorité immédiate pour l'élaboration de stratégies d'adaptation côtière, puisqu'elles se superposent aux tendances du NMM à long terme et aggravent les dangers qui résultent de la seule tendance à la hausse du NMM à plus long terme.

Edward Lorenz, father of chaos theory and butterfly effect, dies at 90

April 16, 2008

Edward Lorenz, an MIT meteorologist who tried to explain why it is so hard to make good weather forecasts and wound up unleashing a scientific revolution called chaos theory, died April 16 of cancer at his home in Cambridge. He was 90.



Prof. Edward Lorenz in 1996
Photo courtesy of MIT News Office

A professor at MIT, Lorenz was the first to recognize what is now called chaotic behaviour in the mathematical modelling of weather systems. In the early 1960s, Lorenz realized that small differences in a dynamic system such as the atmosphere--or a model of the atmosphere--could trigger vast and often unsuspected results.

These observations ultimately led him to formulate what became known as the butterfly effect--a term that grew out of an academic paper he presented in 1972 entitled: "*Predictability: Does the Flap of a Butterfly's Wings in Brazil Set Off a Tornado in Texas*?"

Lorenz's early insights marked the beginning of a new field of study that impacted not just the field of mathematics but virtually every branch of science--biological, physical and social. In meteorology, it led to the conclusion that it may be fundamentally impossible to predict weather beyond two or three weeks with a reasonable degree of accuracy.

Some scientists have since asserted that the 20th century will be remembered for three scientific revolutions--relativity, quantum mechanics and chaos.

"By showing that certain deterministic systems have formal predictability limits, Ed put the last nail in the coffin of the Cartesian universe and fomented what some have called the third scientific revolution of the 20th century, following on the heels of relativity and quantum physics," said Kerry Emanuel professor of atmospheric science at MIT. "He was also a perfect gentleman, and through his intelligence, integrity and humility set a very high standard for his and succeeding generations."

Born in 1917 in West Hartford, Connecticut, Lorenz received an AB in mathematics from Dartmouth College in 1938, an AM in mathematics from Harvard University in 1940, an SM in meteorology from MIT in 1943 and an ScD in meteorology from MIT in 1948. It was while serving as a weather forecaster for the U.S. Army Air Corps in World War II that he decided to do graduate work in meteorology at MIT.

"As a boy I was always interested in doing things with numbers, and was also fascinated by changes in the weather," Lorenz wrote in an autobiographical sketch.

Lorenz was a member of the staff of what was then MIT's Department of Meteorology from 1948 to 1955, when he was appointed to the faculty as an assistant professor. He was promoted to professor in 1962 and was head of the department from 1977 to 1981. He became an emeritus professor in 1987.

Predictability: Does the Flap of a Butterfly's Wings in Brazil Set Off a Tornado in Texas?

Prof. Edward Lorenz
1972

Lorenz, who was elected to the National Academy of Sciences in 1975, won numerous awards, honours and honorary degrees. In 1983, he and former MIT Professor Henry M. Stommel were jointly awarded the $50,000 Crafoord Prize by the Royal Swedish Academy of Sciences, a prize established to recognize fields not eligible for Nobel Prizes.

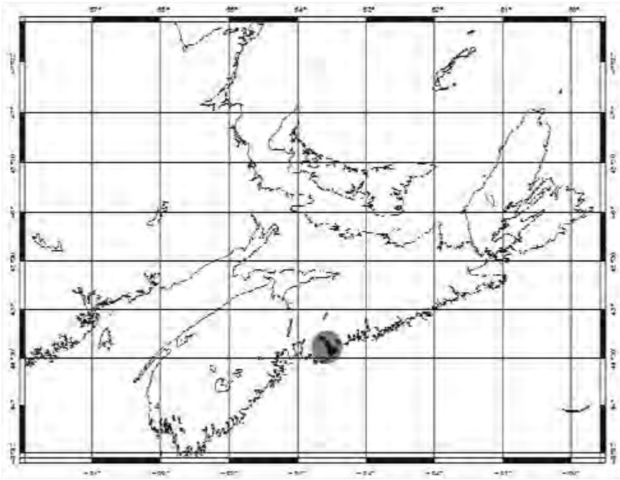
In 1991, he was awarded the Kyoto Prize for basic sciences in the field of earth and planetary sciences. Lorenz was cited by the Kyoto Prize committee for establishing "the theoretical basis of weather and climate predictability, as well as the basis for computer-aided atmospheric physics and meteorology." The committee added that Lorenz "made his boldest scientific achievement in discovering 'deterministic chaos', a principle which has profoundly influenced a wide range of basic sciences and brought about one of the most dramatic changes in mankind's view of nature since Sir Isaac Newton."

During leaves of absence from MIT, he held research or teaching positions at the Lowell Observatory in Flagstaff, Arizona; the Department of Meteorology at the University of California at Los Angeles; Det Norske Meteorologiske Institutt in Oslo, Norway; and the National Center for Atmospheric Research in Boulder, Colorado.

An avid hiker and cross-country skier, Lorenz was active up until about two weeks before his death, his family said. Lorenz is survived by three children, Nancy, Edward and Cheryl, and four grandchildren. His wife, Jane, died in 2001.

Source: MIT website visited April 18, 2008. Reprinted here with the written authorization of the MIT News Office.

7th International Workshop on Unstructured Grid Modelling of Coastal, Shelf and Ocean Flows



The Seventh International Workshop on Unstructured Grid Modelling of Coastal, Shelf and Ocean Flows will be held at the Bedford Institute of Oceanography in Halifax, Nova Scotia, September 17-19 2008.

The workshop website is:

http://wessex.eas.ualberta.ca/~myers/unstructgrid 2008

All announcements for the workshop will be made via the mailing list:

fe-ocean-develop@mailman.srv.ualberta.ca

and to people who have indicated that they wish to receive separate notices.

For more information, see:

http://wessex.eas.ualberta.ca/~myers/FE/fe-list.html.

If anybody would like to receive further notices on the workshop but does not want to subscribe, please contact David Greenberg at

GreenbergD@mar.dfo-mpo.gc.ca.

Abstract Submission
Abstracts should be emailed in plain text or MSWord to

mike.foreman@dfo-mpo.gc.ca

by **June 15, 2008.**

Abstracts should have the form:

1) Title
2) Authors/affiliations/address(email & postal)
3) Abstract (250 word max, no figures).

If using MSWord, font should be 12pt, Times New Roman.

In addition to the usual presentations, discussion sessions and posters, present plans call for a half day session summarizing the state of the art in unstructured modelling that will be open to the wider Halifax scientific community.

We anticipate a small workshop fee that will cover coffee breaks, lunches served on site and the workshop dinner. Receipts will be issued. Weekend expeditions and tours are being investigated. The workshop receives support from Department of Fisheries and Oceans (DFO) and Canadian Meteorological and Oceanographic Society (CMOS).

Previous workshop locations included:

- 2002: Liege, Belgium.
- 2003: Delft, Netherlands.
- 2004: Toulouse, France
- 2005: Bremerhaven, Germany.
- 2006: Miami, USA.
- 2007: London, England.

Previous Workshop Publications:

1) Ocean Modelling Special Issue: The second international workshop on unstructured mesh numerical modelling of coastal, shelf and ocean flows, Delft, The Netherlands, September 23-25, 2003.

2) Ocean Modelling Special Issue: The third international workshop on unstructured mesh numerical modelling of coastal, shelf and ocean flows, Toulouse, France, September 20-22, 2004.

3) Ocean Modelling Special Issue: The sixth international workshop on unstructured mesh numerical modelling of coastal, shelf and ocean flows, London, England, September 19-21, 2007. In prep.

US - Canada Agreement to Work Together on Weather and Climate Research

New Orleans, Louisiana, United States, January 22, 2008 - The National Oceanic and Atmospheric Administration (NOAA) and Environment Canada signed a cross-border agreement to enhance weather and climate monitoring and research.

"With this agreement, NOAA and Environment Canada can broaden our collaboration to enhance health, safety and economic prosperity for our countries and the world," said retired

Navy Vice Adm. Conrad Lautenbacher, Ph.D., under secretary of commerce for oceans and atmosphere and NOAA administrator. "Although our organizations have engaged in a successful relationship for decades, we now have a framework that allows us to explore new opportunities."

The Memorandum of Understanding establishes a formal link between the two organizations, as well as a standing committee with representatives from both countries that will meet regularly to collaborate on cross-border projects.

"International partnerships like this between meteorological services is key to advancing the quality of our weather and environmental forecasting services protecting citizens' health and property," said Mark Warawa, Parliamentary Secretary to Canada's Environment Minister John Baird. "This agreement is another important milestone in our efforts to understand and combat climate change."

House Passes Critical Ocean Observing System Bill

(Washington, D.C.) - On April 1, the U.S. House of Representatives passed the National Integrated Coastal and Ocean Observing Act of 2007. The Act would create an Integrated Ocean Observing System (IOOS) that will monitor and forecast ocean conditions, including the physical, biological and chemical components of coastal waters. The Act would also increase understanding of complex deep ocean and coastal environments and promote the dissemination of information to local policymakers and the public.

An integrated ocean observing system will protect public health through the identification of marine toxins and pollutants in coastal areas as well as improving warnings of tsunamis, hurricanes, El Niño events and other natural hazards. The system will also enhance homeland security, support maritime operations and collect important information needed to address global warming, improve ocean health and provide for the protection, sustainable use and enjoyment of ocean resources.

"*The ocean plays an integral role in our economy, environment and quality of life. Yet our understanding of the ocean and coastal environment is very limited*," said Representative Thomas Allen (D-ME) who introduced the bill. "*We need the equivalent of the national weather service for the ocean and IOOS provides us with that predictive capability for the oceans*," continued Representative Allen.

"*The ocean science community has been working for more than a decade on developing observing systems, which will help us better understand, manage and protect our ocean and coastal resources*," said Robert Gagosian, President and CEO of the Consortium for Ocean Leadership. The Integrated Ocean Observing System was identified as a central ocean priority by the U.S. Commission on Ocean Policy (2003), the Pew Oceans Commission (2004), the Joint Ocean Commission Initiative (2006) and the Ocean Research Priorities Plan and Implementation Strategy (2007). "*Congress took a significant step toward making these recommendations a reality, which will fundamentally change how we study the ocean and transfer information into products and services for the public*," continued Gagosian.

The IOOS bill (H.R.2342) passed the House by voice vote. The Senate has yet to consider its version of the IOOS bill (S.950), which was approved by the Senate Commerce, Science and Transportation Committee last year.

Proceedings of IUGG XXIV General Assembly Perugia, Italy, 2007

All abstracts presented at the XXIV IUGG General Assembly, held in Perugia from July 2nd to the 13th, 2007 are now available on line, including those of IAPSO. The abstracts as pdf files can be viewed and/or downloaded from the www.iugg2007perugia.it web site at the following link: http://www.iugg2007perugia.it/webbook/

Second Symposium on The Ocean in a High-CO_2 World

Registration and abstract submissions are now open for the Second Symposium on “The Ocean in a High-CO_2 World” to be held in Monaco on October 6-9, 2008. The symposium web site can be found at http://www.highco2world-ii.org.

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