Dry spell characteristics over Canada in a changing climate as simulated by the Canadian RCM

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ABSTRACT

Dry spells, defined as extended periods of dry days, can serve as indicators of drought conditions, and are often used in the management of water resource systems, particularly for agriculture. In this study, the Canadian RCM (CRCM) projected changes to dry spell characteristics over Canada, for the April–September period, and their validation in current climate, are presented. Two CRCM integrations are considered: one validation integration for the 1961–2000 period and a transient climate change integration for the 1961–2010 period, corresponding to the SRES A2 scenario. The ability of the model to simulate dry spell characteristics, i.e. mean number of dry days, mean number of dry spells and selected return levels of maximum dry spell durations, and associated errors are assessed through comparison of integrations for the current 1971–2000 April–September period with those observed, derived from the observed precipitation records. Results suggest an underestimation of the mean number of dry days and 10- and 30-year return levels, while the model slightly overestimates the mean number of dry spells, at the grid-cell scale. Analysis of projected changes to dry spell characteristics for the future 2041–2070 and 2071–2100 periods, with respect to 1971–2000 period, suggests significant changes, particularly for the southern Prairies, where both mean number of dry days and return levels of maximum dry spell durations are projected to increase. Furthermore, combined analysis of changes to the amount of precipitation and mean number of dry days also suggests potential increase in drought conditions in future climates in this already drought-prone region for the April–September period. In addition to southern Prairies, this study also suggests significant changes to dry spell characteristics for other regions of Canada.

1. Introduction

There is growing evidence of the impact of climate change on various climate-sensitive sectors of economy, which includes forestry, fisheries and agriculture. Agriculture is Canada’s most important economic activity, even though only a small percentage of the land is suitable for farming. Increased temperatures in the future may provide opportunities for growing higher valued crops, but this may not be possible where changes to regional precipitation patterns lead to insufficient rainfall and more frequent droughts. The viability of many crops is constrained not only by the number of frost-free and growing degree days per year, but also by the frequency and duration of high temperature events that expose crops to damage from heat stress, and the availability of moisture (Zwiers and Kharin, 1998). Therefore, any assessment of climate change impacts on water resource systems should focus on all hydro-meteorological variables that affect water availability, including number of dry/wet days, short and long dry spells and precipitation intensity. According to the Intergovernmental Panel on Climate Change Assessment Reports (IPCC, 2001; 2007), increases in the amount of precipitation are very likely in high latitudes in future climate, while decreases are likely in most subtropical land regions. These changes in the mean precipitation are accompanied by changes in the characteristics of rainfall events such as dry and wet spells (Zwiers and Kharin 1998; Kharin and Zwiers 2000). Tebaldi et al. (2006), from an ensemble of nine Global Climate Models (GCMs) contributing to the Fourth Assessment Report of the IPCC (2007), documented changes to maximum dry spells; in their study, following Frich et al. (2002), a maximum dry spell is defined as the largest number of consecutive days with precipitation less than 1 mm. As discussed in Tebaldi et al. (2006), while drought conditions are the effect of prolonged and complex set of weather conditions, involving several months to years of long precipitation deficits and soil moisture characteristics, dry spells can serve as indicators of drought conditions. Majority of the GCMs used in their study project a flat global and hemispheric average trend for the maximum duration of dry spells, for the lowest emission scenario B1, while significant increases are predicted under A2 and A1B.
scenarios. In addition, study of spatial variability in dry spell duration trends by Tebaldi et al. (2006) suggests shortening of the length of dry spells, in the mid and high latitudes of the northern hemisphere, while the lower latitudes of the northern hemisphere would undergo a tendency towards longer dry spells.

GCMs, because of their still relatively coarse resolution, have difficulties in simulating extreme weather events with the intensity and frequency comparable to what is observed, particularly for precipitation events. Regional Climate Models (RCMs), with their higher spatial resolution, compared to that of the GCMs, allow for greater topographic realism and finer-scale atmospheric dynamics to be simulated and thereby represent a possibly more adequate tool for generating information required for many regional impact and adaptation studies. This improved representation of severe weather phenomena in RCMs has motivated various studies on heavy precipitation and droughts on the basis of RCM simulations for different parts of the world (Seneviratne et al., 2002; Christensen and Christensen, 2007a; Fowler et al., 2005; Eun-Soon and Kwon, 2007; Beniston et al., 2007; May, 2008). Beniston et al. (2007) investigated changes to extreme events that are most likely to affect Europe in forthcoming decades, using a variety of diagnostic methods and RCM integrations produced within the PRUDENCE (Christensen and Christensen, 2007a,b) project. Their study suggests an increase in dry spell durations over southern Iberia, for SRES (Special Report on missions Scenarios) A2 and B2 emission scenarios. Recently, May (2008) also looked at projected changes to dry spell characteristics, i.e. frequency, duration and 30-year return levels of dry spells, among other precipitation extreme variables, over Europe using two 3-member ensembles of simulations with the HIRHAM RCM for the period 1961–1990 and 2071–2100. He used a precipitation threshold of 1.8 mm to differentiate between a dry and wet day and demonstrated that the general pattern of projected changes in the median of the length of dry spells divides the European area in two parts, with a decrease in the length of dry spells in northern Europe and an increase in the central and southern parts of the continent. Another study of changes to dry spell characteristics using RCMs was performed by Eun-Soon and Kwon (2007), over Korea, using RegCM3, for the SRES B2 emission scenario. They used a precipitation threshold of 1 mm to define a wet day and their analysis suggested no significant changes to dry spell characteristics over Korea.

There are no studies, so far, looking systematically at changes to dry spell characteristics over Canada, using RCMs, and we therefore in this study perform a systematic validation of the Canadian Regional Climate Model (CRCM) simulated dry spell characteristics, followed by an assessment of their projected changes, over Canada, for the April–September period. The April–September period was chosen as it covers the growing season and would be of great interest to various economic sectors, particularly the agriculture sector, for impact and adaptation studies.

The paper is organized as follows. Section 2 describes the Canadian RCM and its experimental configuration, observational dataset and the methodology followed in this study. Validation of CRCM-simulated dry spell characteristics is presented in Section 3, followed by projected changes to selected dry spell characteristics in Section 4. Discussion and conclusions are presented in Section 5.

2. Model, experimental configuration, datasets and methods

2.1. Model and experimental configuration

The precipitation field and thereby the dry spells used in this study are simulated by the current operational version of the Canadian RCM, which is the fourth generation of the CRCM. A detailed description of the earlier versions of CRCM can be found in Caya (1996) and Caya and Laprise (1999). The CRCM’s horizontal grid is uniform in polar stereographic projection and its vertical resolution is variable with a Gal-Chen scaled-height terrain following coordinate. The operational version of CRCM shares most of the subgrid-scale physical parameterization package of the global model that provides its driving data for this study: the third-generation Canadian General Circulation Model (CGCM3; McFarlane et al., 2005). This package includes the physically based three-layer Canadian Land Surface Scheme CLASS, version 2.7 (Verseghy, 1991; Verseghy et al., 1993). The moist convection of CRCM follows the Bechtold–Kain–Fritsch’s parameterization (Kain and Fritsch, 1990; Paquin and Caya, 2000; Bechtold et al., 2001). Though the study focuses on Canada, all CRCM simulations were computed on a 200×192 points grid (see inset of Fig. 1a), covering whole of North America and adjoining oceans, with a horizontal grid-point spacing of 45 km and 29 levels in the vertical, ranging from the surface to the model top near 29 km.

A 140-year CRCM integration, spanning the 1961–2100 period, is considered in this study; this integration performs dynamical downsampling of a member of an ensemble of ten CGCM3 simulations to produce climate projection at the regional scale, where the equivalent CO2 and aerosol evolution follows the SRES A2 scenario (IPCC, 2001). Though the simulation spans the 1961–2100 period, this study focuses on the current 1971–2000, future 2041–2070 and 2071–2100 30-year periods. Henceforth, this simulation will be referred to as the ‘climate change simulation/experiment/integration’.

In addition a ‘validation experiment’, i.e. a CRCM simulation forced at the lateral boundaries by ERA40 reanalysis (Uppala et al., 2005) data from the ECMWF, for the 1961–2000 period is also considered; though the simulation spans the 1961–2000 period, in this analysis we consider only the 1971–2000 period, to correspond to the current 1971–2000 period of the climate change simulation analyzed. According to IPCC (2001 and 2007), RCM simulations nested by analyses of observations, or so-called ‘perfect’ boundary conditions, can reveal RCM ‘performance errors’ primarily due to the internal dynamics and physics of the regional model, and should precede any attempt to make climate-change projections. Following this guidance, in this study, we first evaluate the performance of CRCM by comparing the dry spell statistics obtained from the validation experiment with those observed. In addition to regional model’s performance errors, the CRCM climate change simulations will also have additional errors from the nesting CGCM3 data since RCMs are strongly influenced by the large-scale circulation from driving GCMs (Christensen et al., 1997). This ‘boundary forcing error’ can be assessed comparing climate statistics, for the 1971–2000 period, of the climate change and validation simulations.

2.2. Observational dataset

The observed dry spell characteristics are derived from the observed daily precipitation values available from Environment Canada’s precipitation stations network (http://www.loki.qc.ca/DAI/). This network consists of about 9239 currently operational and discontinued precipitation stations with majority of stations concentrated in the southern parts of Canada (Fig. 1a). The length and period of precipitation records vary within the network for the selected April–September period. Average daily observed precipitation for CRCM grid cells is computed from available data by simple averaging of precipitation observed at various stations that fall within a given grid cell; the spatial coverage of the available precipitation stations was such that 2080 CRCM grid cells had at least one precipitation station, which were then subject to further screening with respect to the length of observed record. Those grid cells with at least 21 years of observed daily precipitation record during the period 1971–2000, and with not more than 10 missing values for the April–September period were identified and retained for analysis purposes; the above resulted in 6614 stations that were retained, that are distributed over 872 CRCM grid cells. The
distribution of CRCM grid cells as a function of all available stations and those retained for analysis, following the station selection criterion explained above, is shown in Fig. 1b; the number of precipitation stations per CRCM grid cell retained for analysis varies between 1 and 145, as can be seen from the red bar graph of Fig. 1b. The spatial distribution of retained stations is such that 16.8, 64.1, 82.2, 94.5, 97.4, 99.7 and 99.8% stations lie south of the 45th, 50th, 52nd, 55th, 60th, 70th and 75th parallel, respectively. Thus, the northern high-latitude regions are sparsely covered by the retained precipitation stations.

2.3. Methods

In this study, a dry day is defined as a day with amount of precipitation less than a pre-defined threshold; the choice of this threshold is subjective and in this study precipitation thresholds of 0.5 mm, 1 mm, 2 mm and 3 mm are considered. Further, a dry spell is defined as an extended period of dry days, similar to the definitions used in Beniston et al. (2007), May (2008), Lana et al. (2006), among others. The dry spell characteristics for the April–September period considered include: (1) mean number of dry days, (2) mean number
of dry spells and (3) 10- and 30-year return levels of dry spell durations, defined as the statistical estimate of the maximum dry spell duration that would occur on average once every 10 and 30 years, respectively.

The return levels of dry spell durations are computed using two different approaches: annual maximum (AM) and peaks-over-threshold (POT). In the AM approach, the maximum dry spell duration for the April–September period from each year is considered, and in the POT approach, all durations exceeding a chosen high threshold are considered, or alternatively, the average number of dry spell durations per year (say $\lambda$) is set a priori and the largest $n\lambda$ values are selected, from the $n$ years considered. In this study, the latter approach is adopted for $\lambda = 1$ and $\lambda = 2$. The advantage of the POT approach over the AM approach is that it considers those extreme values that are larger than some of the annual maximum extremes and hence will not normally be considered in the AM approach.

In general, for probabilistic modelling of AM and POT values, a two- or three-parameter distribution function is selected on the basis of a goodness-of-fit criterion. Following the work of Hosking and Wallis (1997), five three-parameter distributions (i.e. the Generalized Logistic (GLO), Generalized Extreme Value (GEV), Generalized Pareto (GPA), Generalized Normal (GNO), and Pearson Type-III (PE3)) are selected for this study. The five selected distributions were fitted to samples of observed AM and POT dry spell durations by the method of L-moments. L-moments are linear combinations of order statistics, and compared to the conventional product moments, they are resistant to the effects of outliers and hence provide robust estimates of distribution parameters. The definitions and methods of computing L-moments of various statistical distributions can be found in Hosking and Wallis (1997). It is customary to select a goodness-of-fit criterion to identify a best fitting distribution from a set of selected distributions. In this work, the L-moment ratio diagrams, which are preferred to ordinary moment ratio diagrams (e.g. Cunnane, 1989), in combination with the model selection criteria of Kroll and Vogel (2002), are used to identify the best fitting distribution. For a three-parameter distribution, an L-moment ratio diagram represents L-kurtosis as a function of L-skewness. The L-moment ratio relations for the five studied distributions and that for the observed maximum dry spell durations for the 872 CRCM grid cells, for the AM and POT cases, for two precipitation thresholds (1 mm and 2 mm), are shown in Fig. 2. For the two precipitation thresholds, as expected, the spread of points is larger for the AM and POT ($\lambda = 1$) cases compared to those

![L-moment ratio relations](image)

Fig. 2. L-moment ratio relations, i.e. L-skewness vs. L-kurtosis relations, for observed extreme dry spell durations, computed at CRCM grid-cell scale, for the AM and POT ($\lambda = 1$ and $\lambda = 2$) cases for two precipitation thresholds (1 mm and 2 mm). The orange dot on each subplot corresponds to the average observed L-skewness/L-kurtosis. Shown superposed are the L-moment ratio relations for the five studied distributions.

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for the POT ($\lambda = 2$) case due to larger sample size in the latter case. The scatter of L-skewness–L-kurtosis for the observed data suggests that more than one distribution could be used to model AM and POT values. The average values of the L-skewness and L-kurtosis for the observed data, for both AM and POT cases, are also shown in Fig. 2. Location of these points suggests that the GEV (GPA) distribution is a strong candidate for modelling AM (POT) values. The model selection criteria of Kroll and Vogel (2002) also support the above. Similar conclusions were reached for the other two precipitation thresholds (0.5 mm and 3 mm; figure not shown). In addition, Coles (2001) demonstrated that the distribution of AM asymptotically converges to GEV and similarly that of POT converges to GPA. We, therefore, in this study, use GEV and GPA distributions for modelling observed and model-simulated AM and POT based dry spell durations; other distribution functions (GLO, GNO and PE3) are not explored further.

To begin with, performance and boundary forcing errors are assessed by comparing dry spell characteristics for the current 1971–2000 April–September period from the validation experiment with those observed, and those from the climate change simulation with the validation experiment, respectively. Projected changes to dry spell characteristics for the 2041–2070 and 2071–2100 future climates are then studied by comparing model-simulated dry spell characteristics in future climates with those for the current climate from the climate change simulation, for the April–September period.

3. Validation of CRCM-simulated dry spells

Several studies, including Brochu and Laprise (2007), Sushama et al. (2006), Music and Caya (2009), and references therein, present validation of various near surface fields simulated by CRCM, and therefore, we only present the validation of dry spells and its characteristics, which is the main focus of this study. As discussed under Section 2.3, the model-simulated dry spell characteristics that are validated include mean number of dry days, mean number of dry spells and 10- and 30-year return levels of dry spell durations, for the April–September period, using AM and POT modelling approaches.

To assess the performance error, mean number of dry days from the validation experiment is compared with those observed for the 1971–2000 period on the top panel of Fig. 3, for four precipitation thresholds (0.5 mm, 1 mm, 2 mm and 3 mm); as already discussed, these precipitation thresholds are used to define dry days. Results suggest that at low precipitation threshold of 0.5 mm, the mean number of dry days is significantly underestimated in the validation experiment; the average underestimation is of the order of 30%. In other words the model simulates more wet days compared to those observed in the validation experiment. However, the model-simulated mean precipitation for the validation experiment, for the April–September period agrees reasonably with those observed (figure not shown), suggesting lower precipitation intensities for the model. With increasing precipitation thresholds, the underestimation of the model-simulated mean number of dry days decreases as can be seen from Fig. 3; the average underestimations at 1 mm, 2 mm and 3 mm precipitation thresholds are 17%, 9% and 5%, respectively. Thus, in general, the negative performance bias, primarily due to the physics of the model, suggests model’s tendency to precipitate more often than observed, leading to an underestimation of the mean number of dry days. Similar tendency has also been reported with other RCMs, e.g. May (2008) comments on the RCM HIRHAM’s tendency to artificially produce light precipitation due to the convective scheme’s tendency to drizzle.

Boundary forcing error is assessed with the aid of the scatter plot of mean number of dry days, for the 1971–2000 April–September period, for the validation and climate change simulations, on the bottom panel of Fig. 3. The points are distributed along the 1:1 diagonal line, suggesting smaller boundary forcing errors; on average a small underestimation in the 1–3 mm range is noted for the climate change simulation, with respect to the validation simulation, for the four precipitation thresholds. Thus, in general, the CRCM performance error associated with the mean number of dry days is larger in magnitude compared to the lateral boundary forcing error from CGCM3.

Fig. 4a compares mean number of dry spells from the validation experiment with those observed for the studied April–September period; figure suggests an overall positive bias, with the model overestimating the mean number of dry spells. This overestimation is on average 6% for 0.5 mm precipitation threshold, and varies between 11 and 13% for the 1–3 mm thresholds. This overestimation of mean number of dry spells is consistent with the underestimation of mean number of dry days linked with the model tendency to precipitate more than observed, i.e. frequent changes between wet and dry spells in the model simulation, discussed earlier. The mean number of dry spells varies in the 20–40 range for 0.5 and 1 mm thresholds, while in the case of 2 and 3 mm thresholds, it varies within a wider 10–40 range; the mean number of dry spells in the 10–20 range is mostly for CRCM grid cells at higher latitudes, which receive very little precipitation and therefore, the duration of the dry spells is much larger than those elsewhere in Canada. The boundary forcing error associated with the mean number of dry spells can be assessed from

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In this section, projected changes to dry spell characteristics are evaluated as differences between the future 2041–2070/2071–2100 period and the current 1971–2000 period of the climate change simulation. It should be noted that the projected changes are presented as absolute differences, however, where appropriate reference is also made to percentage changes. The left panels of Fig. 7 show mean number of dry days for various precipitation thresholds for current 1971–2000 April–September period and their projected changes for future 2041–2070 and 2071–2100 periods with respect to 1971–2000 period are shown in the middle and right panels, respectively. A decrease in the mean number of dry days for northern and central Quebec, and to the west/south-west of the Hudson’s Bay, and the northern and western parts of Canada at 0.5 mm precipitation threshold can be noticed for the two future periods, with the magnitude of projected absolute changes increasing from 2041–2070 to 2071–2100; the percentage decrease in number of dry days varies between 0 and —20% for these northern regions in 2041–2070 period, while they lie in the 0 to —30% range for the 2071–2100 period. This suggests more rainy days with precipitation intensity greater than or equal to 0.5 mm/day in future climates for the northern regions show positive errors.

Overall, reduced lateral boundary forcing errors are noted for the southern regions. Larger differences can be noticed for the higher latitudes, with the climate change integration overestimating particularly the return levels, which was also noticed in the scatter plots discussed earlier.

4. Projected changes to the frequency and intensity of dry spells

In this section, projected changes to dry spell characteristics are evaluated as differences between the future 2041–2070/2071–2100 period and the current 1971–2000 period of the climate change simulation. It should be noted that the projected changes are presented as absolute differences, however, where appropriate reference is also made to percentage changes. The left panels of Fig. 7 show mean number of dry days for various precipitation thresholds for current 1971–2000 April–September period and their projected changes for future 2041–2070 and 2071–2100 periods with respect to 1971–2000 period are shown in the middle and right panels, respectively. A decrease in the mean number of dry days for northern and central Quebec, and to the west/south-west of the Hudson’s Bay, and the northern and western parts of Canada at 0.5 mm precipitation threshold can be noticed for the two future periods, with the magnitude of projected absolute changes increasing from 2041–2070 to 2071–2100; the percentage decrease in number of dry days varies between 0 and —20% for these northern regions in 2041–2070 period, while they lie in the 0 to —30% range for the 2071–2100 period. This suggests more rainy days with precipitation intensity greater than or equal to 0.5 mm/day in future climates for
these regions. At the same precipitation threshold an increase in the mean number of dry days can be noticed for southern Canada. Spatial patterns of projected changes at 1 mm, 2 mm and 3 mm thresholds agree in general to those at 0.5 mm, with the magnitude of absolute changes decreasing from 0.5 mm to 3 mm.

Similar to Fig. 7, Fig. 8 shows mean number of dry spells for current 1971–2000 period and their projected changes for future climates for different precipitation thresholds. A decrease in the number of dry spells from current to future is projected for northern Quebec and for the West Coast and parts of northern Canada, at 0.5 mm threshold. For the same threshold, an increase in the number of dry spells can be noticed for southern regions of Canada. The above spatial patterns of projected changes at 0.5 mm threshold vary from those for the other three thresholds. The spatial patterns of projected changes for precipitation thresholds of 1 mm, 2 mm and 3 mm are more similar, with the northern regions showing an increase in the number of dry spells, while a decrease in the number of dry spells is noted for the southern regions. At 3 mm threshold, the northern regions of Canada, i.e. Yukon, Nunavut, Northwest Territories and north of Quebec, show clearly identifiable coherent regional patterns of increase in the number of dry spells. The projected increases for the higher latitudes are related to the greater moisture holding capacity of the warmer air contributing to greater moisture convergence and more precipitation than in current climate, breaking the longer dry spells observed in current climate into several dry spells of reduced duration. The projected decrease, noted for 1–3 mm thresholds, in the number of dry spells for the southern regions is associated with longer dry spells in future climate, which is also reflected in the return levels discussed below.

The above noted differences in climate change signal for different precipitation thresholds, i.e. 0.5 mm vs. higher thresholds of 1 mm, 2 mm and 3 mm, suggest the need for considering various thresholds in the study of dry spells and cautious interpretation of results based on a single precipitation threshold.

Ten- and 30-year return levels of dry spell durations in current 1971–2000 climate, and their projected changes, at 1 mm and 2 mm thresholds, computed using the POT approach for $\lambda = 1$ are presented in Figs. 9 and 10, respectively. As already discussed in the previous section, the return levels for the POT case are computed using the GPA distribution. For 1 mm threshold, increases/decreases in return levels are widespread over Canada. Coherent regional patterns start to emerge at 2 mm threshold, with projected decrease in return levels for northern regions of Canada and an increase in return levels for the southern regions, particularly southern Prairies. It should be noted that the strength of the climate change signal (positive and negative) increases from the 2041–2070 period to the 2071–2100 period. Projected changes to 10- and 30-year return levels of dry spell durations estimated for the AM and POT ($\lambda = 2$) cases (figure not shown), also show similar results. This part of the Canadian prairies, which corresponds to the Palliser triangle area, often referred to as the...
‘dry belt’, is a drought-prone region even in current climate, with annual average precipitation of the order of 300 mm. The annual evaporation normally exceeds precipitation and the region is more often subject to soil moisture deficits leading to longer lasting droughts (Bruce et al., 2000). The northern parts of the prairie-provinces are covered by boreal forests, while these southern parts are mostly used for agriculture and therefore any projected increase in the dry spell durations, particularly during the growing season, can impact the agricultural sector adversely.

Recently Bonsal and Regier (2006) studied future drought occurrence in southern Canada using Standardised Precipitation Index (SPI) and Palmer Drought Severity Index (PDSI). They obtained slightly different results for the two methods; small positive changes in SPI for majority of climate-change scenarios, while PDSI revealed dramatic increases to the potential for future droughts. They argue that the differences between the SPI and PDSI could be attributed to the fact that the SPI only takes into account precipitation, while the PDSI considers both temperature and precipitation in its calculation. Thus the projected changes to mean annual number of dry days and return levels of dry spell duration are in accordance with the PDSI results of Bonsal and Regier (2006).

To delineate regions of varying sensitivity to climate change, particularly with respect to drought, changes to both total precipitation and temperature need to be considered.
precipitation received during the April–September period and the mean number of dry days for the same period were considered simultaneously. The resulting regions, for the two future periods (i.e., 2041–2070 and 2071–2100) with respect to the current 1971–2000 period are shown on the left and right panels of Fig. 11, respectively. Three distinct regions can be seen for Canada. The southern Prairies stand out as the most sensitive, with decrease in total precipitation received and increase in the mean number of dry days for the studied period. Smaller regions, along southeast Canada also appear to be sensitive based on this classification. Southern Ontario and Quebec, though show an increase in mean number of dry days, are associated with a projected increase in precipitation. For the rest of Canada, projections suggest decrease in mean number of dry days and increase in precipitation amount for the April–September period, making these regions less susceptible to drier conditions in future climates. In addition, while considering changes to precipitation amount and return levels of dry spell duration simultaneously (figure not shown), once again southern Prairies stand out as a sensitive region, with more likelihood of drought-like conditions in future climate.

Fig. 7. Mean number of dry days for the April–September period in current 1971–2000 climate (left panels) for various precipitation thresholds (a–d) and their projected changes for 2041–2070 (centre panels) and 2071–2100 (right panels) future climates.
More detailed analysis, including other drought-related variables such as soil moisture, runoff, etc., is required to understand the impacts on the agricultural sector for the identified sensitive region comprising of southern Prairies. For regions such as northern Quebec, the projected increase in precipitation could favour advancement of vegetation further north of the tree-line, though it is also dependent on other factors such as nutrient content of the soil. However, any detailed study of vegetation advancement further north and associated vegetation-climate interactions would require that vegetation be treated as dynamic and not static as is the case with the current operational version of CRCM.

5. Summary and discussion

Various economic sectors, notably agriculture, are sensitive to changes in the characteristics of dry spells. This article presents results from a systematic study of dry spell characteristics over Canada, for current (1971–2000) and two future (2041–2070 and 2071–2100) climates, using CRCM integrations. A summary of the main results follows:

1. The ability of the CRCM in simulating dry spell characteristics in current climate is evaluated in terms of performance errors (due to the internal dynamics and physics of the model) and

![Fig. 8. Mean number of dry spells for the April–September period in current 1971–2000 climate (left panels) for various precipitation thresholds (a–d) and their projected changes for 2041–2070 (centre panels) and 2071–2100 (right panels) future climates.](image-url)
boundary forcing errors (associated with the errors in the driving data), prior to the assessment of projected changes. The evaluation of performance errors of the dry spell characteristics, i.e. mean number of dry days, mean number of dry spells and return levels of dry spell durations, for four precipitation thresholds (0.5 mm, 1 mm, 2 mm and 3 mm) used to define dry days, suggests negative performance errors (or model underestimation) for both mean number of dry days, and 10- and 30-year return levels of dry spell durations. The underestimation of mean number of dry days decreases with increasing precipitation thresholds. Consistent with these results, validation also suggests an overestimation of the CRCM-simulated mean number of dry spells, i.e. positive performance errors. The boundary forcing errors are smaller in magnitude compared to performance errors for all studied dry spell characteristics.

(2) CRCM projections suggest increase in the mean number of dry days for southern regions of Canada for the studied precipitation thresholds, while the mean number of dry days is projected to decrease over the rest of Canada, in general. Projections also suggest a decrease in the mean number of dry spells for southern regions of Canada, and an increase for other regions of Canada, for higher precipitation thresholds (2 mm and 3 mm). In addition, studied 10- and 30-year return levels of dry spell durations, computed using the AM and POT approaches, for 1 mm and 2 mm precipitation thresholds, suggest an increase in return levels of dry spell durations for southern regions, particularly for southern Prairies, for the 2071–2100 future climate.

(3) Identification of sensitive regions following a combined analysis of changes to total precipitation and mean number of dry days in future climate compared to those of current climate suggests that southern Prairies could be a sensitive region with projected decrease in precipitation and increase in mean number of dry days during the April–September period, which also includes the growing season.

(4) This study has provided first hand information on the vulnerability of various regions in Canada, in the context of future dry spells. However, more in-depth analyses are required to explore further the vulnerable regions.

Though dry spells can be indicators of drought, as discussed in Tebaldi et al. (2006) and Vidal and Wade (2009), other indicators that combine precipitation with temperature or evapo-transpiration and soil moisture may be more appropriate for impact assessments in specific sectors, such as agriculture. In addition to the uni-variate probabilistic analysis of dry spell durations over...
A range of precipitation thresholds performed in this article, it would be useful to explore changes to joint occurrence of severity and duration of dry spells in a multi-variate setting (e.g. Shiau and Modarres, 2009), to develop changes to bi-variate return levels.

It should be noted that in this study the 1971–2000, 2041–2070 and 2071–2100 thirty year periods were considered stationary to derive various return levels of dry spell durations and to study their projected changes. However, it is possible and desirable to do a continuous non-stationary frequency analysis of dry spell durations for the entire time series for the 1971–2100 period using both the AM and POT approaches. Such non-stationary frequency analyses will be considered in the future and will follow the guidelines established in Katz et al. (2002), Sushama et al. (2006) and Khaliq et al. (2006). It is expected that the results of such an analysis would strengthen further the conclusions drawn from the split-sample stationary analyses carried out in this paper.

In addition, the conclusions of this study are based on one RCM and future studies will consider multi-model ensembles to better quantify the uncertainty associated with the projections (Christensen et al., 2007); this will be partly fulfilled with the multi-GCM, multi-RCM and multi-scenario outputs that will be produced by the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al., 2004). Also, additional simulations of the CRCM, that are gradually becoming available, will be considered in the future. Analyses of these additional simulations and multi-model ensembles in a non-stationary bi-variate frequency analysis framework would provide additional insights into future distributions of return levels of dry spell durations and associated severities.

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Fig. 11. Classification of regions based on projected changes to precipitation ($\Delta$precip) and mean number of dry days ($\Delta$drydays), for future 2041–2070 (left panels) and 2071–2100 (right panels) period with respect to the current 1971–2000 period, for (a) 0.5 mm, (b) 1 mm, (c) 2 mm and (d) 3 mm precipitation thresholds.

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