The Role of Soil Moisture–Atmosphere Interaction on Future Hot Spells over North America as Simulated by the Canadian Regional Climate Model (CRCM5)

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ABSTRACT

Soil moisture–atmosphere interactions play a key role in modulating climate variability and extremes. This study investigates how soil moisture–atmosphere coupling may affect future extreme events, particularly the role of projected soil moisture in modulating the frequency and maximum duration of hot spells over North America, using the fifth-generation Canadian Regional Climate Model (CRCM5). With this objective, CRCM5 simulations, driven by two coupled general circulation models (MPI-ESM and CanESM2), are performed with and without soil moisture–atmosphere interactions for current (1981–2010) and future (2071–2100) climates over North America, for representative concentration pathways (RCPs) 4.5 and 8.5. Analysis indicates that, in future climate, the soil moisture–temperature coupling regions, located over the Great Plains in the current climate, will expand farther north, including large parts of central Canada. Results also indicate that soil moisture–atmosphere interactions will play an important role in modulating temperature extremes in the future by contributing more than 50% to the projected increase in hot-spell days over the southern Great Plains and parts of central Canada, especially for the RCP4.5 scenario. This higher contribution of soil moisture–atmosphere interactions to the future increases in hot-spell days for RCP4.5 is related to the fact that the projected decrease in soil moisture caused the soil to remain in a transitional regime between wet and dry state that is conducive to soil moisture–atmosphere coupling. For the RCP8.5 scenario, on the other hand, the future projected soil state over the southern United States and northern Mexico is too dry to have an impact on evapotranspiration and therefore on temperature.

1. Introduction

Land is one of the key components of the climate system, and the role of soil moisture–atmosphere interactions and feedbacks in modulating and/or amplifying extreme climate events has been demonstrated in several studies (Oglesby and Erickson III 1989; Atlas et al. 1993; Fischer et al. 2007a,b; Hirschi et al. 2011; Mueller and Seneviratne 2012). For instance, Fischer et al. (2007b) associated a negative soil moisture anomaly with the 2003 extreme heat wave event over Europe through reduced latent heat cooling. Similarly, Oglesby and Erickson III (1989) and Atlas et al. (1993) demonstrated the contribution of the land surface state, particularly dry soil moisture, to the 1988 drought over the United States via reduced local evaporation and increased sensible heating, which resulted in warmer air temperature and enhanced subsidence aloft. A notable influence of the land surface state on climate, particularly related to soil moisture anomalies, is limited to certain regions of the globe, generally referred to as soil moisture–atmosphere coupling hot spots. These hot spots are regions characterized by their soil moisture state that is low enough to control evapotranspiration variability and also large enough to have sufficient evapotranspiration that can thus affect climate.

Though several global (e.g., Koster et al. 2006) and regional (e.g., Diro et al. 2014) modeling studies have identified strong soil moisture–atmosphere coupling over hot-spot regions, there are still considerable uncertainties regarding the spatial and temporal characteristics of soil

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moisture–precipitation and soil moisture–temperature coupling. Studies so far, in general, demonstrate that the strength of soil moisture–temperature coupling is higher and more robust than that of soil moisture–precipitation coupling. There is also a consensus on the role of soil moisture in modulating temperature variability, with studies showing an important contribution of soil moisture variability to temperature variability, particularly during the summer months. The impact of soil moisture on extreme temperature events has also been demonstrated by many studies [Diro et al. (2014) and the references there in]. On the other hand, soil moisture–precipitation coupling is less well understood compared to soil moisture–temperature coupling, partly because of the complex interactions, including boundary layer processes, governing this association [Seneviratne et al. 2010].

In the context of a changing climate, associated with enhanced greenhouse gas (GHG) concentrations in the atmosphere, it is likely that the characteristics of soil moisture–atmosphere coupling, particularly the spatial distribution and coupling strength, may change. For example, wet regions in current climate that will be subject to decreases in soil moisture in future climate can acquire the characteristics of transitional regions and become soil moisture–temperature coupling hot spots. Consequently, the land surface state becomes a key player for modulating the temperature variability and extreme temperature events, such as heat waves, as discussed in Diffenbaugh et al. (2007) and Hirschi et al. (2011). The study of temperature extremes such as hot spells and projected changes to their characteristics is of critical importance, given that the impact of climate change often manifests itself not only as shifts in mean temperature (Ballester et al. 2010) but also as changes in the variability (Fischer and Schär 2009), which may lead to frequent extreme events. Studying extreme temperature events is also important, as they have considerable impacts, such as an increased risk of heat-related mortality (Hajat et al. 2007; Zanobetti and Schwartz 2008).

The underlying mechanisms for the increase in extreme temperature characteristics in future climate will vary with region. Meehl and Tebaldi (2004), for instance, associated the future changes in extreme temperature events over North America and Europe to changes in atmospheric circulation: more specifically, to the intensification of midtropospheric heights in future climate. Other studies, such as Diffenbaugh et al. (2005), have emphasized the interaction between local processes and the large-scale forcing as an important factor, responsible at least partly for the projected changes in extreme temperature events. Seneviratne et al. (2006) reported that soil moisture feedbacks are the main drivers for the projected increase in temperature variability over eastern Europe in future climate. Recently, Seneviratne et al. (2013) using five GCMs and Lorenz et al. (2016) using six GCMs from the Coupled Model Intercomparison Project, phase 5, (CMIP5) investigated the impact of soil moisture on the surface climate for the representative concentration pathway (RCP) 8.5 scenario. Seneviratne et al. (2013) noted that, associated with the projected drier soil conditions, the extreme temperatures increased substantially over many parts of the world, including the Great Plains of North America. Their results, however, emphasized the impact of long-term soil moisture changes on climate rather than the role of interannual soil moisture variability alone on the atmosphere. Lorenz et al. (2016) assessed the impact of the long-term trend as well as the year-to-year variability of soil moisture on extreme events and found that the future drying trend affects the frequency and intensity of temperature extremes, whereas future changes in soil moisture variability affect more the frequency than the intensity of temperature extremes over most regions of the world.

Given these results, it is relevant to undertake a comprehensive and detailed assessment of the impact of future warming on the land surface state and its subsequent impact on temperature extremes, such as hot days and hot spells across North America in future climate for different emission scenarios. This paper therefore investigates the projected changes to the characteristics of soil moisture–atmosphere coupling over North America for different RCP scenarios and its impact on selected temperature extremes using the fifth-generation Canadian Regional Climate Model (CRCM5). In particular, we are interested in the following research questions: What changes to the summer spatial pattern of soil moisture–atmosphere coupling can be expected in future climate for different RCPs? To what extent can projected changes in extreme temperature characteristics such as the number of hot days and hot-spell frequency and duration be related to the projected changes to the land surface state and to changes in soil moisture–atmosphere interactions and feedbacks?

In this study, two sets of experiments using CRCM5 are performed. In the first set of experiments, soil moisture–atmosphere interaction is enabled, while it is curtailed in the second set of experiments. Results are analyzed for two selected 30-yr time slices, i.e., 1981–2010 and 2071–2100. The analysis of these simulations allows us to identify the role of future changes in soil moisture–atmosphere coupling on projected changes of temperature extremes.

The rest of the paper is arranged as follows. Section 2 describes the model, design of experiments, and methodology. Analysis of soil moisture–atmosphere coupling
hot spots in the CGCM-driven CRCM5 simulations and a possible connection between soil moisture–atmosphere coupling and extreme temperature characteristics in current climate are discussed in section 3. Section 4 explores projected changes to the soil moisture–atmosphere coupling strength in future climate, and the impacts of these changes on the projected change of temperature extremes are presented in section 5. Finally, a summary and conclusions are provided in section 6.

2. Model and methods

a. Model description and experimental design

The regional climate model used in this study is CRCM5 (Martynov et al. 2013), which is the limited-area version of the Global Environment Multiscale (GEM) model (Côté et al. 1998). CRCM5 has a non-hydrostatic dynamical core and uses Arakawa C grid staggering in the horizontal and a hybrid terrain-following vertical coordinate. The numerical scheme is a two-time-level, semi-Lagrangian, implicit scheme. The convective schemes of Kain and Fritsch (1992) and Bélaire et al. (2005), for deep and shallow convections, respectively, are used. The resolvable large-scale precipitation is computed following Sundqvist et al. (1989). Radiation is parameterized by correlated- k solar and terrestrial radiation of Li and Barker (2005). The planetary boundary layer scheme follows Benoit et al. (1989) and Delage (1997), with some modifications as described in A. Zadra et al. (2012, personal communication). Lakes, both resolved and subgrid scale, are represented by the Flake model (Mironov et al. 2010). The land surface scheme in CRCM5 is the Canadian Land Surface Scheme (CLASS) (Verseghy 1991, 2009; Verseghy et al. 1993), which allows a flexible soil layer configuration; in this study 26 soil layers that extend up to 60 m are considered. CLASS includes prognostic equations for energy and water conservation for the soil layers and a thermally and hydrologically distinct snowpack where applicable.

The study domain covers the whole of North America and adjoining oceans, as shown in Fig. 1. It consists of 212 × 200 grid points (including the blending and halo zones), at 0.44° horizontal resolution and has 56 levels in the vertical, as in Diro et al. (2014). As mentioned earlier, two sets of experiments are performed with CRCM5. The first set consists of six coupled (i.e., with evolving soil moisture) regional simulations, while the second set consists of matching pairs of six uncoupled (prescribed soil moisture) simulations (Table 1); the matching coupled and uncoupled simulations share the same boundary conditions. The six simulations in each set correspond to two current climate (1981–2010) simulations driven by the second generation of the Canadian Earth System Model (CanESM2; Arora et al. 2011) and by the Max Plank Institute for Meteorology Earth System Model (MPI-ESM; Giorgetta et al. 2013), while the other four are future climate (2071–2100) simulations, corresponding to the two RCP scenarios RCP4.5 and RCP8.5 (Van Vuuren et al. 2011), driven by CanESM2 and MPI-ESM. The simulations driven by CanESM2 and MPI-ESM will be referred to as CRCM5_CanESM2 and CRCM5_MPI-ESM, respectively. It must be noted that the matching current (1981–2010)
and future (2071–2100) periods in the coupled simulations set are indeed coming from one long simulation spanning the 1950–2100 period. In the coupled simulations, soil moisture is allowed to interact with the atmosphere at every time step, while, in the uncoupled simulations, soil moisture for each layer is prescribed with 3-hourly climatological values, and hence the soil moisture–atmosphere interaction is effectively turned off. The uncoupled simulations are run only for the current (1981–2010) and future (2071–2100) periods, unlike the coupled simulations, which are run continuously from 1950 to 2100. The prescribed 3-hourly climatological values of soil moisture in the uncoupled simulations are computed from the matching coupled simulations for current (1981–2010) and future (2071–2100) periods. In addition, we also consider coupled and uncoupled CRCM5 simulations driven by ERA-Interim (i.e., near-perfect boundary condition) for 1981–2010, against which CRCM5_CanESM2 and CRCM5_MPI-ESM results are compared.

b. Extreme temperature indices

The various hot-spell metrics considered in this study are discussed here. It must be noted that there are different definitions and thresholds used for hot spells in literature (Zhang et al. 2011). In this study, a hot-spell event is defined as a period of three or more consecutive hot days, with a hot day defined as a day with daily maximum temperature (Tmax) exceeding a predefined threshold. The threshold used is the 90th percentile of Tmax for the historical coupled simulation following Diro et al. (2014) and Jeong et al. (2016). This threshold varies with the calendar day and grid point. Since soil moisture–atmosphere interactions are particularly important during the summer season, given the high evaporation fraction, all the analyses are carried out for the June–August (JJA) months. The following three hot-spell metrics were computed for each grid point: the hot-spell frequency (HSF) (i.e., the number of hot-spell events per summer); the number of hot-spell days per summer (HSD); the maximum duration of hot-spell event (MxDHS).

c. Coupling strength measure

The soil moisture–temperature coupling strength is evaluated as in Diro et al. (2014) using the variance method, which is briefly discussed below. In this study, we are analyzing Tmax rather than the daily mean temperature, as soil moisture–atmosphere coupling is stronger during daytime (Hirsch et al. 2014).

In the variance method, the contribution of the interactive soil moisture to the interannual variability of the mean summer daily maximum temperature (Tmax) is computed as

\[ \Delta \sigma^2_{T_{\text{max}}} \left(\%\right) = \frac{\sigma^2_{\text{coupled}} - \sigma^2_{\text{uncoupled}}}{\sigma_{\text{coupled}}} \times 100\% , \]

where \( \sigma_{\text{coupled}} \) and \( \sigma_{\text{uncoupled}} \) are the interannual standard deviations of mean summer Tmax for the coupled and uncoupled simulations, respectively. Higher values of \( \Delta \sigma^2_{T_{\text{max}}} \) imply a strong contribution of land (soil moisture) to the interannual variability of Tmax. The statistical significance of the coupling strength is assessed using the F-test (Von Storch and Zwiers 2001). A paired Student’s t test is also used to assess the significance of the difference between two sets of simulations.

d. Quantifying the contribution of soil moisture–atmosphere interactions to the projected changes in extremes

The change in the frequency or maximum duration of hot spells can be split into that due to changes in soil moisture–atmosphere interactions associated with the variability in soil moisture and that due to changes in other factors (e.g., change in SST, change in large-scale circulation, and change in mean soil moisture) as follows:

\[ \Delta \nu(\text{Future}_{\text{coupled}} - \text{Current}_{\text{coupled}}) = \Delta \nu(\text{Future}_{\text{uncoupled}} - \text{Current}_{\text{uncoupled}}) + \Delta \nu(\text{Future}_{\text{coupled-uncoupled}} - \text{Current}_{\text{coupled-uncoupled}}), \]

where \( \nu \) represents the specific variables we are interested in this study, such as HSD, HSF, MxDHS.

In the above equation, the left-hand side represents the total change in the seasonal mean of the variable characteristic that we are interested in. The first term on the right-hand side of the equation is the change due to large-scale forcing and other factors, including change in soil moisture climatology, while the second term is associated with change in soil moisture–atmosphere interactions due to the suppression of soil moisture variability.

3. Soil moisture–atmosphere coupling in current climate

The characteristics of the climatological soil moisture–atmosphere coupling during summer, over North America, in CRCM5, when driven by ERA-Interim, were analyzed in Diro et al. (2014), which suggests that the soil moisture–temperature coupling strength is relatively high over the transitional regions of the Great Plains, consistent with the results of Koster et al. (2006). The soil moisture variability over these transitional regions...
was found to be important both for intraseasonal and interannual variability of surface variables, particularly temperature.

The near-surface variables simulated by CRCM5 when driven by MPI-ESM and CanESM2 for the current climate over North America were validated extensively in Separović et al. (2013). One of their main conclusions was that both MPI-ESM- and CanESM2-driven CRCM5 simulations reproduce reasonably well the surface climate of North America. However, for the JJA season, they noted that CanESM2-driven simulations exhibit a warm bias over the central United States and Canada and a cold bias over Mexico, whereas MPI-ESM-driven CRCM5 simulations are closer to observations, with the exception of the northwestern part of the continent, where it shows a cold bias.

Since hot-spell characteristics are considered in this study, the ability of the model in simulating these characteristics when driven by reanalysis and CGCMs are assessed here. Figure 2 shows the climatology of hot-spell characteristics for current climate from observation and CRCM5 simulations driven by reanalysis. Also shown are the difference between the GCM-driven simulations and the ERA-Interim-driven one. It must
be noted that the threshold of the 90th percentile of $T_{\text{max}}$ used to extract the hot-spell days is based on the respective dataset. The observed data used to compute hot-spell characteristics are those of Maurer et al. (2002) for the contiguous United States and Hutchinson et al. (2009) and Hopkinson et al. (2011) for the Canadian land points south of 60°N. For both datasets, the 1981–2010 period is considered to match the simulation period. Generally, both model simulations and observation show similar patterns for hot-spell duration and frequency, with high values along the western part of North America and the southeastern United States. Model simulations and observation also agree that the regions with smaller values for hot-spell days and frequency are situated over the central and northeastern parts of North America. However, some biases are noted. For instance, CRCM5 simulations, especially when driven by CanESM2, overestimate the number of hot-spell days over the western United States and over Alaska and slightly underestimate over the southeast United States and over northern Canada. MPI-ESM-driven simulations also overestimate the number of hot-spell days over northern Canada and underestimate over the southeast United States.

Since this study focuses on projected changes to soil moisture–atmosphere coupling, it is useful to assess the characteristics of soil moisture–temperature coupling in CRCM5 in the current climate when driven by CanESM2 and MPI-ESM at the lateral boundaries. Figure 3 shows the summer coupling strength for maximum daily temperatures in CRCM5 simulations driven by ERA-Interim, MPI-ESM, and CanESM2, as measured by the variance approach (see section 2c), together with the interannual variability, as measured by the interannual standard deviation. The results indicate that the locations of the dominant soil moisture–temperature

FIG. 3. Present-day (top) interannual standard deviation of temperature (°C) and (bottom) soil moisture–temperature coupling strength as measured by the percentage of variance (%) for CRCM5 driven by (left) ERA-Interim, (center) MPI-ESM, and (right) CanESM2. Color shading in (bottom) represents areas that are statistically significant at the 0.05 level.
coupling hot spots are found between the climatically wet areas of eastern North America and the climatically dry areas of western North America, covering the Great Plains and northern Mexico, which is consistent with the GLACE result of Koster et al. (2006) and Guo et al. (2006). It is interesting to note that the high interannual variability of temperature over the Great Plains of the United States tends to collocate with the region of high soil moisture–temperature coupling. Although the dominant coupling region is similar in the ERA-Interim as well as in the two GCM-driven simulations, some differences can be noted in the spatial extent of this region. For instance, the northward extent of the strong soil moisture–atmosphere coupling hot spot is inhibited in the MPI-ESM-driven CRCM5 simulation compared to that of the CanESM2-driven one. This is consistent with the higher precipitation and soil moisture values and slightly lower interannual variability of soil moisture over the region in the MPI-ESM-driven simulation compared to the CanESM2-driven one, as shown in Fig. 4. This implies that temperature variability in the MPI-ESM-driven CRCM5 simulation for the high-latitude regions is more influenced by the large-scale atmospheric processes rather than those related to soil moisture–atmosphere interactions and feedbacks. Likewise, in the MPI-ESM-driven simulation, the strong coupling region extends zonally into the western United States compared to the CanESM2-driven and ERA-Interim-driven simulation and is due to the higher soil moisture and evapotranspiration values (Fig. 4) in MPI-ESM-driven simulations for this region; the higher values of soil moisture in MPI-ESM-driven simulations will increase the evaporative cooling effect for the dry regions over the southwestern United States, as evapotranspiration over this region is soil moisture limited.

It is interesting to note that the dominant hot spots, such as over the Great Plains, tend to be collocated with regions where soil moisture exhibits the highest
variability, particularly for the CanESM2-driven simulation (Fig. 4). This reiterates the fact that soil moisture–temperature coupling is stronger when two conditions are fulfilled (i.e., soil moisture values are representative of a transitional zone and exhibit high interannual variability).

The overall model ability in reproducing the present-day hot-spell characteristics and the consistency of the model results with the results from previous modeling studies for all driving fields justifies the use of the model to study projected changes to these characteristics and linkages with soil moisture–atmosphere coupling.

4. Projected changes to soil moisture–atmosphere coupling

In this section, projected changes to the geographical distribution of soil moisture–atmosphere coupling hot spots and to the coupling strength in future climate for two selected RCP scenarios are investigated.

The variance method indicates that, in future climate, there will be important shifts in the location of the soil moisture–atmosphere coupling regions, as well as in the coupling strength, over the Great Plains and over the southern Prairies, depending on the RCP scenario and the driving CGCM (Fig. 5). For instance, over the eastern parts of the United States, CanESM2-driven simulations suggest an expansion of the coupling hot spot, whereas the MPI-ESM-driven simulations suggest a decrease for these regions. This dependence of the spatial pattern on the driving data is tied to the projected changes in the soil moisture pattern. Figure 6 (first and second row) shows projected changes to the vertically integrated and top-layer soil moisture, for both CanESM2- and MPI-ESM-driven simulations, for both RCP scenarios. The integrated soil moisture is projected to decrease over most of the domain, especially over central and western Canada in all CRCM5 simulations. For the eastern part of the United States, CanESM2-driven CRCM5 simulations project a decrease in soil moisture, while some increases in the top-layer soil moisture are noted over the western United States. This decrease in soil moisture over the eastern edge of the Great Plains and over the southern Canadian Prairies, in the CanESM2-driven simulation, is

![Diagram](image-url)
FIG. 6. Projected changes to (top to bottom) mean-summer vertically integrated soil moisture (mm), liquid soil moisture content of the top 10-cm-thick soil layer (%), evapotranspiration (mm day$^{-1}$), precipitation (mm day$^{-1}$), and temperature (°C) for (left to right) MPI-ESM-driven and CanESM2-driven CRCM5 coupled simulations for RCP4.5 and RCP8.5 scenarios. Color shading represents areas with changes that are statistically significant at the 0.05 level. For (bottom), the change is statistically significant at the 0.05 level for all grid points.
also reflected in the future decreases in summer precipitation, in addition to the obvious increase in near-surface air temperature (Fig. 6, fourth and fifth row). The correlation between soil moisture and evapotranspiration is projected to increase (Fig. 7 over the eastern and northern part of the domain (in particular in the CanESM2-driven simulations), which implies that future decrease in soil moisture for the climatologically wet eastern United States regions will switch the evapotranspiration regime of this region from energy limited to soil moisture limited. These relationships between the reduction in soil moisture and the enhanced CO₂ concentration in the summer season over Canada and the Great Plains are in agreement with past studies (e.g., Manabe and Wetherald 1987; Manabe et al. 2004; Leipprand and Gerten 2006). In the MPI-ESM-driven simulation, however, the projected changes of soil moisture over the eastern United States are modest, since projected increases in precipitation for this region compensate for the increase in evapotranspiration (Fig. 6, third and fourth row). These projected small increases in soil moisture over the energy-limited evapotranspiration regions of the eastern United States are in line with the projected decrease in soil moisture–temperature coupling. On a similar note, a slight decrease in moisture in the top 10-cm soil layer is noticed over the semiarid region of the western United States, which is already in a soil moisture–evaporative regime, but the evapotranspiration variability becomes less able to influence the temperature variability, and hence it is not surprising that the coupling strength will become weaker there in the future.

Overall, the largest increment in the coupling strength (especially to the east and west of the Great Plains) is noted for the CanESM2-driven simulation for RCP4.5 (Fig. 5), although the projected changes to soil moisture are higher for RCP8.5. This is because the change in coupling strength depends not only on the change in mean soil moisture but also on the change in the interannual variability of soil moisture. Over the eastern Great Plains, the CanESM2-driven simulation suggests an increase in the interannual variability of soil moisture in future climate, for RCP4.5, and this contributes to the large increase in the coupling strength for this region compared to the simulation for the RCP8.5 scenario. Similarly, the variability in the top-layer soil moisture is significantly reduced in the RCP8.5 scenario (not shown) over the semiarid regions (e.g., northern Mexico), which leads to a decrease in the variability of evapotranspiration and a weakening of the soil moisture–temperature coupling strength.

The above results focused on the impact of projected changes to soil moisture–atmosphere coupling on the variability of summer mean temperature. We now investigate the impact of soil moisture changes on the extreme temperature characteristics presented in section 2b by examining the difference in the hot-spell days and maximum duration of hot spells between coupled and uncoupled simulations.

Figure 8 shows the difference in the number of summer hot-spell days between coupled and uncoupled CRCM5 simulations for current and future climates. It must be noted that the number of hot-spell days for the future climate and for the uncoupled simulations is identified using the same 90th-percentile threshold determined based on the matching coupled simulation for current climate. The figure illustrates that, over most of the simulation domain (with the exceptions of coastal areas and the regions surrounding the Great Lakes), the number of hot-spell days is significantly higher in the coupled simulations than in the uncoupled simulations. This implies that soil moisture variability amplifies the hot-spell days irrespective of the driving model. The fact that the impact of soil moisture on hot-spell days is significant (at the 0.05 level) not only just over the Great Plains but over wider regions, including the wet regions of the eastern part of North America, suggests that wet regions can become hot spots of soil moisture–temperature coupling during extreme hot years, as reported in Diro et al. (2014) and Hirschi et al. (2011).

Figure 8 also illustrates that the impact of soil moisture variability on hot-spell days becomes amplified in the future climate, especially over central Canada and over the southern United States for the RCP4.5 scenario. For the RCP8.5 scenario, although the impact of soil moisture on hot-spell days is amplified and expands toward the high-latitude regions, results for the southern United States are sensitive to the driving data.

The difference in the maximum duration of hot-spell days between coupled and uncoupled simulations for current and future climates is shown in Fig. 9. It indicates that drier soil conditions in future climate also lead to longer hot-spell duration. The result also suggests that the impact of soil moisture on the hot spells of longest duration is expected to increase under the RCP8.5 compared to the RCP4.5 scenario. All CRCM5 simulations suggest that future maximum duration of hot spells is closely linked to soil moisture, and this strong association is observed over a wider area, particularly in CanESM2-driven simulations.

5. Quantification of the contribution of soil moisture–atmosphere coupling to future extremes

The results discussed so far have shown the increased importance of soil moisture–atmosphere interaction
both from seasonal mean and extremes perspectives. However, it is not clear to what extent the changes in soil moisture–atmosphere interaction contribute to the projected changes in extremes compared to all other potential forcings. Figure 10 shows the projected changes in hot-spell days and the decomposition of these changes into those due to soil moisture–atmosphere coupling and that due to changes in all other factors, such as large-scale forcing and mean climatology of soil moisture (see section 2d).

Figure 10 (top panel) shows the projected change to the number of hot-spell days for MPI-ESM- and CanESM2-driven simulations and for RCP4.5 and RCP8.5 scenarios. The projections clearly indicate an increase in the number of hot-spell days throughout the domain for all CRCM5 simulations. As expected, the largest change in hot-spell days is for the simulations that correspond to RCP8.5. The projected changes depend on the driving CGCM, with the largest changes to the hot-spell days being associated with the CanESM2-driven simulation. The larger increase in the CanESM2-driven CRCM5 simulation is because CanESM2 projects higher temperature increases than the MPI-ESM, as illustrated in Separović et al. (2013). The spatial distribution of the projected changes in hot-spell days indicates maximum changes for the southern part of the domain. This is in agreement with past studies (e.g., Giorgi 2006; Jeong et al. 2014) that reported Central America, including Mexico and the southern United States, to be drier and warmer in the future, based on multiple GCM and RCM outputs.

Examination of the contributions from the local soil moisture–atmosphere coupling due to soil moisture variability and those due to other factors, including changes in soil moisture trend, suggest that the projected changes in the number of hot-spell days is mostly due to changes in factors other than soil moisture–atmosphere coupling, including the large-scale forcing, particularly over the southern and western regions of the landmass for the RCP8.5 scenario. The contribution of soil moisture–atmosphere coupling change is small for the higher-emission scenario (RCP8.5), especially for the CanESM2-driven simulation for the above regions (Fig. 10). There are, however, other regions, such as most of Canada, the Great Plains, and the northern United States, where the changes in soil moisture–atmosphere coupling contribute substantially to the projected increases in hot-spell days, as shown in Fig. 10 (bottom row). It is interesting to note that the contribution of soil moisture–atmosphere coupling changes to the change in HSD over the southern part of the domain is larger for the RCP4.5 compared to the RCP8.5 scenario. For the RCP8.5 scenario, the change in soil moisture–atmosphere coupling contributes up to 30% of the projected increase in hot-spell days, with the contribution mostly limited to high-latitude regions. For RCP4.5, the change in soil moisture–atmosphere coupling contributes 40%-50% of the projected increases in hot-spell days over the Great Plains and central Canada in the CanESM2-driven simulation. For the MPI-ESM-driven simulation, the fractional contribution of land is even higher, in particular over the southern United States and northern Mexico, where the contribution is more than 50% of the projected increases in hot-spell days. This illustrates that the response of soil moisture–atmosphere coupling (and its impact on extreme temperature characteristics) to greenhouse gas warming is nonlinear and varies regionally. In addition to the
emission scenario, the result is also sensitive to the driving model. For instance, for the same emission scenario, the contribution of soil moisture–atmosphere interactions to the projected increases in the number of hot-spell days in the CanESM2-driven simulation is generally smaller compared to the MPI-ESM-driven simulation, particularly over the southern United States and northern Mexico. This is because the CanESM2-driven CRCM5 projects drier soil conditions and a higher temperature increase compared to the MPI-ESM-driven simulations, and, as a result, the evaporation from the drier soil is too small to affect the climate in the CanESM2-driven simulation.

Similar analysis is applied to hot-spell frequency (not shown) and maximum duration of hot spells (Fig. 11). The results suggest that the impact of soil moisture–atmosphere coupling changes contribute to an increase in the number of hot-spell days and the maximum duration of hot spell over most regions of North America. The locations of these regions vary slightly depending on the driving GCM and RCP scenario. For the maximum duration of hot spells, the contribution of changes in soil moisture–atmosphere coupling is generally higher for MPI-ESM, for the RCP4.5 scenario. The change in soil moisture–atmosphere coupling contributes more than 50% of the projected increase in the maximum hot-spell duration over the southwestern United States, the southern Great Plains, and the eastern Prairies in the CRCM5 simulation driven by MPI-ESM for the RCP4.5 scenario. The change in large-scale forcing, on the other hand, contributes more over the east and west coasts of North America.

Overall, soil moisture–atmosphere coupling contributes to the projected increase in the frequency (not shown) and maximum duration of hot spells over the northern part of the domain, such as over central regions.
Canada, in particular when the model follows the RCP4.5 pathway. As central Canada and the eastern United States are greatly affected by future decrease in soil moisture in summer, these regions will be in soil moisture–limited evaporation regimes (Fig. 7), where soil moisture–atmosphere coupling becomes instrumental in affecting the surface climate. This is consistent with the increase in the mean and variability of projected extreme temperature events in these regions. The expansion and shift of soil moisture–atmosphere coupling hot spots to climatologically wet zones over North America was previously reported by Dirmeyer et al. (2013). It has to be noted that there are also regions where the changes in the land state lead to decreases in the contribution of soil moisture–atmosphere coupling to extreme temperature (e.g., over the present-day transitional zones) in the CanESM2-forced simulations, notably for the RCP8.5 scenario. This could be due to two factors. The first one is related to the decrease in soil moisture in these regions that can alter the land state from a transitional to a dry regime and therefore leading to weaker soil moisture–atmosphere coupling. The second factor could be a decrease in the interannual variability of soil moisture in the future climate, which could reduce the frequency of the evapotranspiration level that is high enough to have a significant impact on surface climate and yet low enough to be soil moisture limited. For MPI-ESM-driven simulations (for the RCP4.5 scenario), on the other hand, the contribution of soil moisture–atmosphere coupling to future extremes is not suppressed over the southern United States and northern Mexico, as the moisture stays in the transitional state both in current and future climates.

It is also important to consider the impact of future change in soil moisture–atmosphere coupling on the variability of future hot-spell characteristics, in addition to the impact on the mean hot-spell characteristics. Such an analysis is performed for the Canadian Prairies, as...
it is one of the regions where a consistent increase in the contribution of soil moisture–atmosphere coupling strength is noted across both scenarios and driving GCMs. Figure 12 shows the frequency distribution of the differences in the number of hot-spell days and maximum hot-spell duration between coupled and uncoupled simulations, for the Canadian Prairies (100°–110°W, 48°–55°N), for current and future climates. This figure indicates a broadening and shift in the central tendency of the distribution of the differences in hot-spell days and maximum duration for the future climate compared to the current climate. This suggests that the contribution of soil moisture–atmosphere coupling in future affects more the change in the variability than the change in the mean. This increase in the variability is robust, as all the CRCM5 simulations show a consistent picture irrespective of the driving field or the emission pathways they follow. Therefore, the change in soil moisture–atmosphere coupling and interactions is more likely to increase the future intense hot spells.

6. Summary and conclusions

In this study, the role of soil moisture–atmosphere coupling in modulating temperature extremes is assessed in the context of a changing climate over North
America. In particular, we examine how projected changes to soil moisture–temperature coupling will influence projected changes to hot-spell characteristics by comparing two sets of CRCM5 simulations, with and without soil moisture–atmosphere coupling. Each set consists of present (1981–2010) and future (2071–2100) simulations, driven by two CGCMs (CanESM2 and MPI-ESM) with high and modest climate sensitivity. For future climate, two concentration pathways (RCP4.5 and RCP8.5) are considered.

The soil moisture–atmosphere coupling characteristics in the CRCM5 simulations, when driven by CanESM2 and MPI-ESM, are first assessed for the current climate. The results indicate that the location of the coupling hot spots and the coupling strength in the CGCM-driven simulations are generally similar to those of the reanalysis-driven simulations and previously published results, despite small differences in the magnitude and spatial extent. The mean soil moisture–atmosphere coupling hot spots in future climate are projected to expand farther north. The coupling hot spots also extend to the eastern part of the continent in the CanESM2-driven simulations, associated with drier soil conditions, which results in a regime shift in evapotranspiration, from energy driven in current climate to soil moisture driven in future climate.

In absolute terms, the enhanced maximum duration of hot spells due to soil moisture–atmosphere interaction is projected to increase in future climate over the southern United States and over central Canada for both driving GCMs and RCP scenarios. However, the relative
contribution of the projected changes to soil moisture–atmosphere coupling (compared to the changes to all other forcings, including change in mean soil moisture) to the projected increases in hot-spell characteristics appear to be sensitive to the driving field and to the choice of RCP scenario. The change in soil moisture–atmosphere interactions contributes significantly (i.e., by more than 50%) to the projected increases in hot-spell days over central Canada and over the Great Plains, especially for MPI-ESM and for the RCP4.5 scenario. Generally, the biggest contribution of the changes in soil moisture–atmosphere coupling to the increases in hot-spell characteristics is for the RCP4.5 scenario, particularly for the southern United States and Mexico. In fact, for these regions, for the RCP8.5 scenario, the projected changes to soil moisture variability partially offset the projected increases in hot-spell characteristics as a result of other factors. For the Canadian Prairies, the strengthening of soil moisture–atmosphere coupling contributes more to the increase in the variability of hot-spell characteristics than mean characteristics, which implies future increases in rare severe temperature events for the region because of increases in soil moisture–atmosphere coupling there.

This study focused only on the impact of soil moisture variability changes on soil moisture–atmosphere coupling and did not consider those due to changes in mean soil moisture levels alone. Although this study highlights that soil moisture–related hot spells, in particular hot spells of longest duration, are expected to increase in future warmer climate, further work to assess the combined effect of projected changes to the mean and variability of soil moisture on extreme events for different RCP scenarios will be useful. The other main limitation of this study is that the results are based on a single regional climate model. Past studies (e.g., Koster et al. 2006) have demonstrated that soil moisture–atmosphere coupling and its projected changes can be model dependent. Further work using multiple regional climate models, driven by multiple CGCMs and concentration pathways, therefore, would be beneficial to quantify better

**FIG. 12.** Distribution of difference in (top) the number of HSD and (bottom) MxDHS between coupled and uncoupled simulations for current and two future scenarios for (left) CanESM2- and (right) MPI-ESM-driven CRCM5 simulations over the Prairies (110°–100°W, 48°–55°N). The distribution sample is constructed from the number of grid points and the number of years.
the uncertainties associated with the role of projected changes in soil moisture–atmosphere coupling on future temperature extremes.

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