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Key Points:

- A wetland model in the Canadian prairies, based on surface water balance and ecoregion, shows reliable prediction of wetland extents
- Future projected wetland distribution under climate change exhibits strong spatial heterogeneity and seasonal variability
- Eastern Canadian prairies face complex challenges due to wetland drying whereas wetlands become more abundant in western in future climate

Supporting Information:

Supporting Information may be found in the online version of this article.

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Heterogeneous Changes to Wetlands in the Canadian Prairies Under Future Climate

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Abstract Numerous wetlands in the prairies of Canada provide important ecosystem services, yet are threatened by climate and land-use changes. Understanding the impacts of climate change on prairie wetlands is critical to effective conservation planning. In this study, we construct a wetland model with surface water balance and ecoregions to project future distribution of wetlands. The climatic conditions downscaled from the Weather Research and Forecasting model were used to drive the Noah-MP land surface model to obtain surface water balance. The climate change perturbation is derived from an ensemble of general circulation models using the pseudo global warming method, under the RCP8.5 emission scenario by the end of 21st century. The results show that climate change impacts on wetland extent are spatiotemporally heterogenous. Future wetter climate in the western Prairies will favor increased wetland abundance in both spring and summer. In the eastern Prairies, particularly in the mixed grassland and mid-boreal upland, wetland areas will increase in spring but experience enhanced declines in summer due to strong evapotranspiration. When these effects of climate change are considered in light of historical drainage, they suggest a need for diverse conservation and restoration strategies. For the mixed grassland in the western Canadian Prairies, wetland restoration will be favorable, while the highly drained eastern Prairies will be challenged by the intensified hydrological cycle. The outcomes of this study will be useful to conservation agencies to ensure that current investments will continue to provide good conservation returns in the future.

1. Introduction

The Prairie Pothole Region (PPR) contains millions of small wetlands (also known as prairie potholes) within topographic depressions across five states in the United States (Iowa, Minnesota, North Dakota, South Dakota, Montana) and three provinces in Canada (Alberta, Saskatchewan, Manitoba). These wetlands provide important ecosystem services, including improving water quality, water regulation, and supporting biodiversity (Gleason, 2008; Hayashi et al., 2016; Johnson et al., 2010; Niemuth et al., 2014). The PPR is not only known as one of the most important landscapes for breeding waterfowl in North America (Batt et al., 1989), but it also provides crucial habitats for nesting and migration for other wetland- and grassland-associated birds (Beyersbergen et al., 2004; Niemuth et al., 2008; Rich et al., 2004). As a result, the PPR is the focus of conservation programs in both Canada and the United States. The major conservation partnerships of this region (i.e., the Prairie Habitat Joint Venture [PHJV] and Prairie Pothole Joint Venture [PPJV]) recognize that wetlands in the PPR face threats from land-use conversion to cropland and possible threats from climate change-related drying (PHJV, 2014; PPJV, 2017). Niemuth et al. (2014) hypothesized that land-use change may be more influential on wetlands and wildlife than direct effects of climate change. Incorporating land use into projections of the effect of climate on wetlands suggests that regions most climatically suitable for wetlands in the future may not coincide with areas that show lower land-use pressures (Sofaer et al., 2016).

In the PPR, prairie wetlands exist because of key interactions among topographic, geological, and climatic conditions (Hayashi et al., 2016; van der Kamp & Hayashi, 2009). These local depressions were formed by clay-rich glacial until deposition from the continental ice sheet during Pleistocene glaciation.

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Local topographic variation (hollow and hummock) favors the convergence of surface runoff and shallow groundwater lateral flow in depressions. In addition, cold winters allow snow accumulation on the ground and spring snowmelt is an important source of surface runoff filling these closed depressional wetlands (Ireson et al., 2013). The PPR also has a semi-arid climate, with wetland water most abundant in May after snowmelt but continuously evaporating through the summer. The duration of inundation/permanence of prairie wetlands varies widely, depending on the water balance (Hayashi et al., 2016), which is influenced by factors such as seasonal precipitation, snowmelt runoff, and recharge from shallow groundwater. Moreover, water in nearby depressions can be connected by ephemeral streams during wet conditions through a "fill-and-spill" mechanism, suggesting dynamic connectivity of surface runoff interacting with water availability and depressional topography (Ehsanzadeh et al., 2012; Mekonnen et al., 2014; Shaw et al., 2012). These surface water expansions and contractions respond to climate and vary spatially (Vanderhoof & Alexander, 2016; Vanderhoof et al., 2018).

Observational studies have documented recent changes in climatic conditions, for example, temperature and precipitation, and hydrological regime shifts, with implications for waterfowl populations in various parts of the PPR (e.g., Dumanski et al., 2015; Niemuth et al., 2010). Since the early 1990s, an extended period of high precipitation has caused a hydrological regime shift to a novel "wet continuum," with corresponding increases in pond numbers, lake levels, streamflow amount, soil moisture (SM), as well as waterfowl populations in the southern PPR (South and North Dakota) (McKenna et al., 2017; Niemuth et al., 2010, 2014). On the other hand, the western PPR (mostly in the western Canadian Prairies, Alberta) has shown a decreasing trend in precipitation, glaciers, streamflow (St. Jacques et al., 2013) and number of inundated ponds in July (Niemuth et al., 2014). These contrasting trends in the recent observation record have been demonstrated by G. Liu and Schwartz (2012), in a reconstruction of surface water body numbers based on moisture residual in the last five years in 27 locations across the PPR.

Modeling studies have attempted to project future wetlands and hydrological conditions across the PPR from a range of possible climate change scenarios (Forbes et al., 2011; Johnson et al., 2005; Kienzle et al., 2012; MacDonald et al., 2012). These studies have simulated a baseline condition under current climate and added a delta climate change to temperature or precipitation for future climate. For example, in Johnson et al. (2005), the climate change scenarios were designed with a temperature warming of 3°C and a precipitation increase or decrease of 20%, applied uniformly across the PPR. In Forbes et al. (2011), MacDonald et al. (2012), and Kienzle et al. (2012), delta climate changes in temperature and precipitation were derived from monthly means of general circulation model (GCM) ensembles and were imposed upon current station observations in three watersheds in the western PPR. Despite the range of climate change projections considered, this type of delta climate change method may be unsuitable for wetland water balance studies as it lacks constraints on energy and moisture conservation in the coupled atmosphere and land system and is unable to capture possible combined extreme hydroclimatic conditions as in processes-based models.

Other modeling studies have established statistical relationships between long-term climatic conditions and wetland surveys to generate predictions of wetland distributions in the PPR. For example, Niemuth et al. (2014) and Herfindal et al. (2012) developed linear regression models to predict wetland counts as a function of climate (precipitation and temperature) and other (e.g., plant phenology, land use) variables. Garris et al. (2015) used 35 climate variables from GCM outputs from CMIP4 in a linear model paired with an artificial neural network technique to predict a potential increase of wetland areas in Southwest Minnesota. Sofaer et al. (2016) used yet another approach, choosing climate outputs downscaled from 10 GCMs in CMIP5 and forcing them through a land surface hydrology model (Variable Infiltration Capacity, VIC, Liang et al., 1994). They built a statistical relationship between 15 hydrological variables from VIC gridded output and wetland density in the US portion of the PPR, using the overall surface water balance (i.e., precipitation minus potential evapotranspiration) as the most sensitive predictor of wetland density.

The coarse resolution of GCM outputs (∼50–100 km) is not suitable for modeling prairie wetlands, and discrepancies among GCM projections restrict the reliability of future wetland projections. Additionally, GCM-projected future precipitation forecasts are highly uncertain depending on the choice of convection parameterization (i.e., the mathematical description of the convection processes within each model grid cell; Kendon et al., 2017; Prein et al., 2015). This is problematic as precipitation is the key water input for prairie wetlands.

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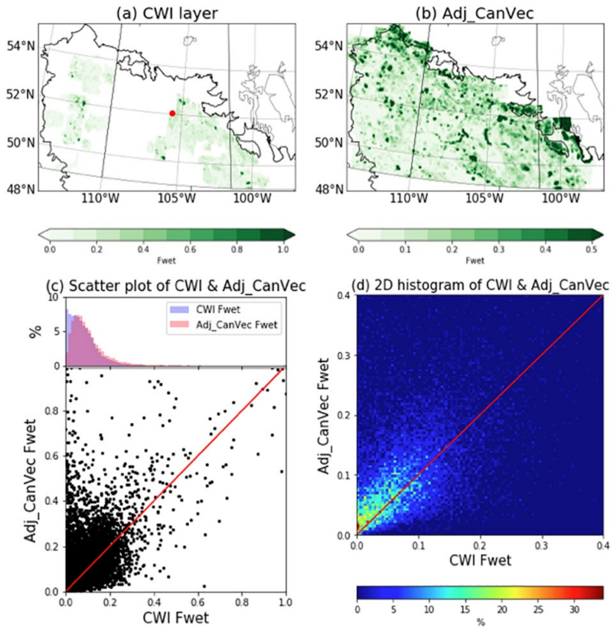

Figure 1. (a) F_{wet} (0–1) spatial distribution from the Canadian Wetland Inventory (CWI); (b) F_{wet} (0–1) spatial distribution from Adjusted CanVec layer (Adj_CanVec), a modeled wetland data set; (c) scatter plot (bottom) and histogram (top) of F_{wet} of the CWI (blue) and Adj_CanVec (red) and (d) a 2D histogram of F_{wet} from 0 to 0.4. The red dot in Figure 1a represents the location of the St. Denis National Wildlife Area in Saskatchewan.

Using GCM outputs to study the impact of climate change on wetlands requires downscaling. Recent progress in dynamical downscaling using high-resolution regional climate models (RCMs) with the pseudo global warming (PGW) method provides us with a surrogate climate change scenario for studying hydrological responses to climate change (Schär et al., 1996). The PGW method usually consists of two dynamical downscaling simulations. The first simulation is from a retrospective data set of the current climate (control simulation, CTRL). The second applies a climate change perturbation derived from an ensemble of GCMs to the current climate to generate a future climate scenario using RCM, referring to as the PGW simulation. The PGW method has multiple advantages. The CTRL simulation is reasonably reliable compared to direct downscaling from GCMs and allows detailed climate and hydrological process studies (Schär et al., 1996). Additionally, dynamical downscaling with a high-resolution convection-permitting regional climate model (CPRCM) improves precipitation forecast as well as provides detailed representation of surface properties. Multiple studies have shown great potential of the PGW method downscaled with a CPRCM in studying atmosphere processes, hydrological responses, and model intercomparison in the climate science community (Fang & Pomeroy, 2020; Li et al., 2019; C. Liu et al., 2017; Musselman et al., 2017; Prein et al., 2016; Zhang et al., 2020). It offers a novel and powerful approach for studying climate change and its impacts on the hydrological conditions for prairie wetlands.

The purpose of this study is to investigate the impacts of climate change on the future abundance and distribution of wetlands in the Canadian portion of the PPR (hereafter, the Canadian prairies), using the PGW method. More specifically, our objectives are to: (a) model the impacts of climate change on spatial distribution of wetlands as well as seasonal variation under the PGW climate scenario, focusing on water availability (van der Kamp et al., 2016); (b) explain these changes by water balance analysis; (c) explore potential joint effects of climate change and historical drainage patterns on future wetland ecosystem services and conservation policies. These are achieved by applying the hydroclimatic outputs from previous CPRCM simulations in the Noah-MP land-surface hydrology model and statistically fitting a fractional wetland index for each grid point in the Canadian prairies in high-resolution (4 km). Results of this study have important implications for wetland conservation, especially for decision making on prioritizing conservation investments across the Canadian prairies. For example, the PHJV uses spatial targeting to maximize the return on conservation investments (PHJV, 2014). Understanding how the patterns (including wetland density) that drive current conservation delivery prioritization may change in the future is key to ensuring that investments made now deliver benefits in perpetuity or give conservation organizations the information needed to adapt their programs to changing conditions.

2. Data and Models

2.1. Wetland Data Sets

The Canadian Wetland Inventory (CWI) classifies wetlands according to the Canadian Wetland Classification System (National Wetlands Working Group, 1997) and, in the prairies, delineates wetland basins from stereo pairs, with a minimum mapping unit of 0.02 ha. In the protocol used, the wetland extent spans the wet meadow vegetation zone to the deepest point of the basin and represents the depressional area capable of holding water. Shapefiles from the CWI were compiled into a high-resolution single geodatabase for the Canadian prairies to represent wetland fractional area in 4-km grid cells (F_{wet}, Figure 1a). Given the challenges in mapping small wetland features, the CWI represents the best available map of prairie wetlands, though it has incomplete coverage of the Canadian prairies.

For a product with prairie-wide coverage, we used a modeled spatial layer, the Adjusted CanVec layer (hereafter, "Adj_CanVec"; Figure 1b). CanVec is a vector data set developed by Natural Resources Canada

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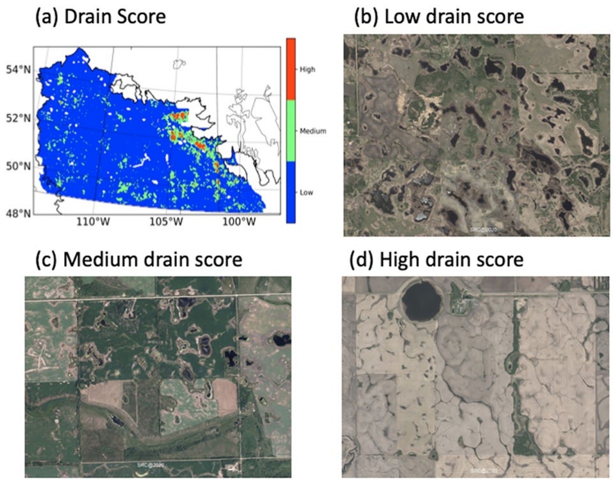

Figure 2. (a) A qualitative drain score map based on density of drainage ditches with (b–d) examples of the three drain scores (photos are from the Saskatchewan Geospatial Imagery Collaborative).

(Government of Canada, 2008). It has good spatial coverage but does not capture all small wetlands and has variable scale (~1:10,000–1:50,000) and accuracy. Ducks Unlimited Canada used CanVec hydrography and water saturated soils features, Soil Landscape of Canada data (Soil Landscapes of Canada Working Group, 2007), and CWI to generate predictive equations to scale CanVec 3.0 data to the high-resolution CWI data in the prairies. Because it is difficult to separate out wetlands and lakes in the CanVec data, the Adj_CanVec includes some non-wetland waterbodies such as shallow prairie lakes. A layer of MODIS-derived water mask was applied to remove large water bodies at 4-km grid scale (n = 174 grid cells).

Figures 1a and 1b show the distribution of F_{wet} from CWI and Adj_CanVec in the Canadian prairies. The Adj_CanVec shows a high F_{wet} close to the northern boundary of the PPR in the aspen parkland ecoregion. Figure 1c is a scatter plot of F_{wet} from these two data sets with their histogram on the top. The majority of the data points are below 0.3, while Adj_CanVec has a longer tail of high F_{wet}. Figure 1d focuses on the two data sets of F_{wet} from 0 to 0.4. It is evident that most data points are smaller than 0.3 and Adj_CanVec has a tendency for higher F_{wet} than the CWI.

Due to the strong wet-dry cycles in the prairies, wetland extent varies both through space and time (G. Liu & Schwartz, 2012). However, the CWI and Adj_CanVec are both static products meant to represent long-term conditions and are thus not suitable for evaluating the temporal performance of the statistical model. Therefore, we investigated temporal changes in ponding depth at the St. Denis National Wildlife Area (SDNWA, 52°12′N 106°5′W) in Saskatchewan, Canada (red dot in Figure 1a). Although the site is relatively small in area (4 km^2), it contains hundreds of wetland ponds of various sizes and permanences and long-term monitoring records since 1968 (Bam et al., 2019). To study the temporal wetland dynamics in the SDNWA, the ponding depth records from 140 ponds were used to calculate the change in depth (exact value−all-time mean) at this site. Ponding depth and F_{wet} both reflect moisture conditions at this site and, hence, can provide some reference for evaluating the model performance in this study (see Section 3.1).

Moreover, a supplemental analysis was conducted to show the interannual variation between model simulated F_{wet} and open water fraction in the Smith Creek Watershed (50°50′N 101°34′W) in Southeast Saskatchewan (Figure S5). The Smith Creek Watershed is a long-term established research site for wetland hydrology in the Canadian prairies, though it has experienced high wetland loss due to anthropogenic drainage (Dumanski et al., 2015; Pattison-Williams et al., 2018). The open water fraction in the Smith Creek Watershed was estimated by Multiple Endmember Spectral Mixture Analysis (Roberts et al., 1998), a remote sensing technique to detect open water features in an area (see Text S1 for detailed methods).

Wetland drainage plays a significant role in the human modification of prairie landscapes. The Prairie Habitat Monitoring Program has collected data on the density of drainage ditches in the Canadian prairies. Figure 2 shows a qualitative wetland drainage score, based on the density of agricultural surface ditches as detected through aerial photography and high-resolution satellite imagery (for detailed methods and score descriptions see Appendix 11 in PHJV, 2014). Low drain score areas show minimal evidence of anthropogenic drainage whereas high drain scores exhibit extensive ditching and related drainage. Three examples of drain score photos are included in Figure 2: (b) a low drain score, most wetlands remain intact; (c) a medium drain score, many small wetlands have been drained; (d) a high drain score, most wetlands have been drained and converted to cropland.

To answer the third objective of this study, a joint analysis of both historical drainage conditions and future wetland projections was conducted by: (a) calculating the ΔF_{wet} under extreme conditions, using the 5th and 95th percentile as indicators for extreme dry and wet conditions under climate change; (b) overlaying the ΔF_{wet} with the three drain score categories. A threshold condition of $\left|\Delta F_{wet}\right| > 0.1$ was applied to limit the analysis to areas with substantial projected change. Combining these two data sources can reveal areas

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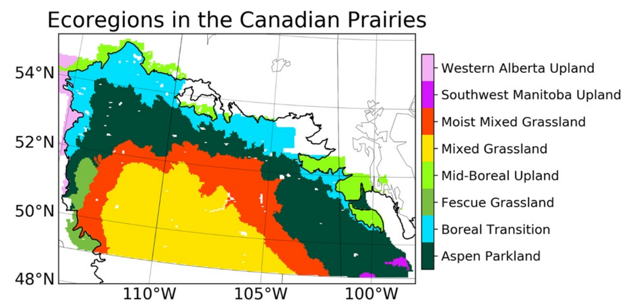

Figure 3. Ecoregions in the Canadian Prairies. Black contour outlines the Prairie Pothole Region and the filled colors represent the eight ecoregions as used in the wetland model. The areas where Adjusted CanVec layer data are unavailable are blank.

where combined effects of climate extremes and level of anthropogenic drainage will result in abundant or impoverished wetland extent to inform designing conservation policies.

2.2. Study Domain and Ecoregions in the Canadian Prairies

Wetland density varies across the PPR, influenced by both geographic and climatic factors. Figure 3 shows eight major ecological regions in central Canada, as defined by the Ecological Land Classification (Statistics Canada, 2017). Ecoregions categorize broad landscapes based on distinctive regional factors including climate, physiography, vegetation, and soil, and thus have the potential to explain spatial variation in wetland area not covered by hydrological or climatological variables. The ecoregions represented in Figure 3 only included those where there was overlapping coverage with the CWI. Ecoregions not represented in the CWI were either excluded from analysis (Lake Manitoba plain) or recoded to an adjacent ecoregion (cypress upland reclassified as mixed grassland, Wabasca lowlands, and interlake plain recoded as mid-boreal uplands). Reclassified grid cells represented less than 1% of all grid cells. These eight ecoregions were used in modeling of F_{wet} (Section 2.4).

2.3. Climate Scenarios and Surface Water Balance

The climate scenarios in this study were obtained from high-resolution (4 km) regional climate simulations in the Contiguous United States and Southern Canada, using the Weather Research and Forecasting (WRF, Skamarock et al., 2008) model (referred to as CONUS WRF, C. Liu et al., 2017). The CONUS WRF simulations contain two paralleled climate scenarios, the current climate (CTRL) and the future climate change scenario, generated using the PGW method (Schär et al., 1996). For the CTRL simulation, the initial and boundary conditions were from a 6-h ERA-Interim reanalysis data set (Equation 1). For the PGW simulation, the initial and boundary conditions were created by adding a climate change perturbation, derived from an ensemble of GCMs by the end of 21st century in RCP8.5 emission scenario, upon the ERA-Interim reanalysis (Equation 2) (see C. Liu et al., 2017 for the full list of GCMs ensemble).

The climate change perturbation was applied to multiple variables, including wind, geopotential height, temperature, specific humidity, sea surface temperature, soil temperature, sea level pressure, and sea ice (Equation 3) (C. Liu et al., 2017). The perturbation in these fields impacted large-scale planetary waves and associated thermal dynamics, while synoptic scale weather events remain structurally constrained by the boundary conditions in terms of frequency and intensity (Rasmussen et al., 2011; Schär et al., 1996). Both CTRL and PGW simulations were dynamically downscaled from above initial and boundary conditions, using the WRF model, and the simulations span from October 01, 2000 to October 01, 2013 (C. Liu et al., 2017) at convection-permitting resolution (4 km). The PGW method has gained popularity in the climate science and hydrology communities, as it concomitantly allows certain processes to be examined in isolation, such as snowfall and snowpack (Musselmen et al., 2017; Rasmussen et al., 2011), mesoscale convection systems (Li et al., 2019; Prein et al., 2016), land-atmosphere interactions (Zhang et al., 2018), and groundwater responses to climate change (Zhang et al., 2020).

$$\mathrm{CTRL} : \mathrm{WRF}_{\mathrm{input}} = \mathrm{ERA} - \mathrm{Interim} \tag{1}$$

$$\mathrm{PGW} : \mathrm{WRF}_{\mathrm{input}} = \mathrm{ERA} - \mathrm{Interim} + \Delta\mathrm{CMIP5}_{\mathrm{RCP8.5}} \tag{2}$$

$$\Delta\mathrm{CMIP5}_{\mathrm{RCP8.5}} = \mathrm{CMIP5}_{2071-2100} - \mathrm{CMIP5}_{1976-2005} \tag{3}$$

The hourly output data from CONUS WRF, including temperature, precipitation, humidity, wind, pressure, short and long-wave radiation, were used to drive a land-surface model (LSM), Noah-MP (Niu et al., 2011; Yang et al., 2011) with groundwater component (Fan et al., 2007; Miguez-Macho et al., 2007), to simulate the hydrological cycle in the study domain. The Noah-MP LSM is a physical process-based model, which explicitly simulates major storage, such as snow water equivalent (SWE) and SM, and hydrological processes, including snow accumulation, sublimation, evaporation, runoff, and groundwater recharge. Snow is a key water source for prairie wetlands at the beginning of snowmelt seasons. The Noah-MP snow model simulates the snowpack for up to three layers according to the snow depth and snow cover fraction as determined by snow density, depth and ground roughness length. The snow surface energy balance is calculated separately over two semitiles of the grid cell, vegetated, and bare ground. The snow albedo scheme is adopted from the CLASS model (Verseghy, 1991), which accounts for snow age, grain size, and accumulated debris on the snow surface. We included an evaluation of model simulated snow processes in the Canadian prairies in the supporting information (Figure S3). Furthermore, the Noah-MP LSM is coupled with a dynamic groundwater model, enabling two-way interactions between SM and an underlying unconfined aquifer, as well as lateral flow from surrounding grid cells. The groundwater dynamics were reasonably simulated and evaluated in Zhang et al. (2020) against multiple well observations in the PPR.

In this study, we used the Noah-MP LSM output SM to represent surface water balance and compute a fractional index (soil moisture content, SMC) as a key input to forecast spatial wetland distribution in the Canadian prairies. The surface water balance can be represented as:

$$\Delta \mathrm{SM} + \Delta \mathrm{SNOW} = \mathrm{PR} - \mathrm{ET} - \mathrm{SR} - \mathrm{G} \tag{4}$$

$$\mathrm{SMC} = \frac{\theta}{\theta_{\mathrm{SAT}}} \tag{5}$$

The change in SM storage (ΔSM) is calculated by volumetric SM times soil depth ($\Delta \mathrm{SM} = \Delta\theta \cdot z$, where z is a 2-m soil layer). Collectively, ΔSM and snow (ΔSNOW) are a product of precipitation (PR), evapotranspiration (ET), surface runoff (SR), and groundwater recharge (G). The fractional SMC is calculated from the volumetric SM (θ) divided by saturated SMC (θ_{SAT}). θ varies from 0 to θ_{SAT}, so that SMC varies from 0 to 1. θ_{SAT} is a parameter determined by soil types and can be found in a parameter look-up table in the Noah-MP LSM: (https://github.com/NCAR/hrldas/blob/master/hrldas/run/SOILPARM.TBL).

2.4. Model of Wetland Fraction

In this study, a generalized additive model (GAM) was used to estimate the relationship between F_{wet} and hydrological and ecological covariates. GAMs accommodate a variety of response distributions/link functions and allow for flexible, additive effects of predictor variables (Hastie & Tibshirani, 1986). The following statistical model was fitted in R (R Core Team, 2020) using the mgcv package (Wood, 2011):

$$g\left(E\left(F_{\mathrm{wet}}\right)\right) = s\left(\mathrm{SMC}\right) + \mathrm{ER} \tag{6}$$

We used a binomial distribution and logistic link of wetland fraction (i.e., $g(p) = \ln(p/(1-p))$, a smooth function of SMC (s(SMC)), and included ecoregion (ER) as a factor predictor variable in the model to allow for different baseline wetland fractions (or intercepts) among the eight ecoregions. More model details are provided in the supporting information (Figure S1). The fitted model was used to predict current wetland fraction (F_{wet}_CTRL), which was evaluated against Adj_CanVec data in the Canadian prairies. SMC is the only hydrological variable in this model and it can be computed over different timescales (e.g., monthly or seasonal). It is assumed that, over the long term, SMC is the net result of hydrological processes from Equation 4 including precipitation, snowmelt, evapotranspiration, runoff, and groundwater recharge. The SMC input for Equation 6 was averaged from March to August, representing a mean moisture condition of the warm season; hence, the modeled F_{wet} would be a seasonal averaged wetland distribution. Finally, to study the impacts of future climate change, we substituted SMC from the future climate model scenario (PGW) to predict future wetland fraction (F_{wet}_PGW). The difference between F_{wet}_PGW and F_{wet}_CTRL can be attributed to the impacts of climate change.

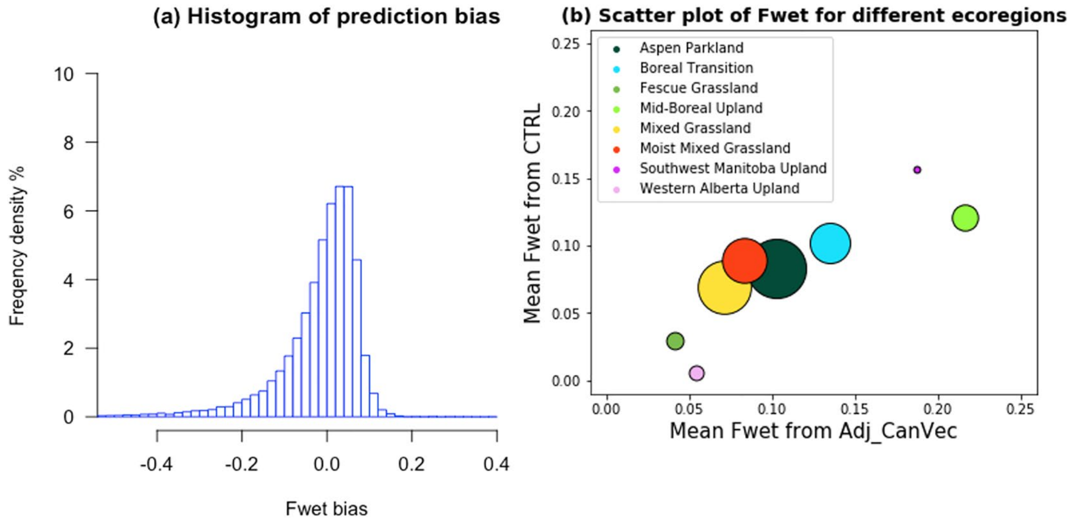

Figure 4. (a) Histogram of the model bias (F_{wet}_CTRL-F_{wet}_Adj_CanVec) showing the relative frequency density of grid cells in the Canadian prairies; (b) scatter plot of mean F_{wet}_CTRL compared with mean F_{wet} from Adj_CanVec by ecoregion. Point sizes are proportional to the square root of sample sizes. Adj_CanVec, Adjusted CanVec layer; CTRL, control simulation.

3. Results

3.1. Validation and Sensitivity of the GAM Model

Figure 4 shows the evaluation results from F_{wet}_CTRL, predicted by the GAM, and the Adj_CanVec, at the grid (Figure 4a) and ecoregion scale (Figure 4b). The average ecoregion F_{wet}_CTRL tends to be lower than average F_{wet} from Adj_CanVec, but they covary positively, with both indices similarly ranking the ecoregions with respect to wetland fraction. The root-mean-square-error of the model prediction in current climate is 0.102 and for 98% of the grids, abs (F_{wet}_CTRL-Adj_CanVec) < 0.1.

As SMC and ecoregions are the two predictors in the GAM, wetlands in different ecoregions may respond differently to climate change impacts. In order to test the sensitivity of modeled F_{wet} by ecoregion, we artificially added a 1% change to the input SMC, with the changes resulting in F_{wet} solely attributable to the ecoregions' intercept-adjustments. Figure 5 shows the aggregated change in F_{wet} in eight ecoregions in the Canadian prairies with perturbed 1% SMC. Given that the statistical model fitted is additive in the effects of ecoregion and (*s*(SMC)), the perturbed change may translate into nonlinear responses in F_{wet}. For the whole domain, the model-predicted F_{wet} increased at twice the rate of the perturbed change in SMC in

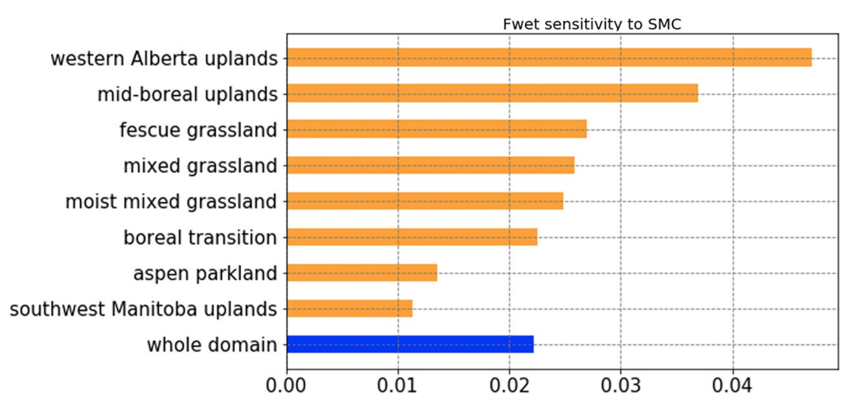

Figure 5. Bar plot of change in F_{wet} relative to a 1% increase in soil moisture content (SMC) for the entire domain and eight ecoregions.

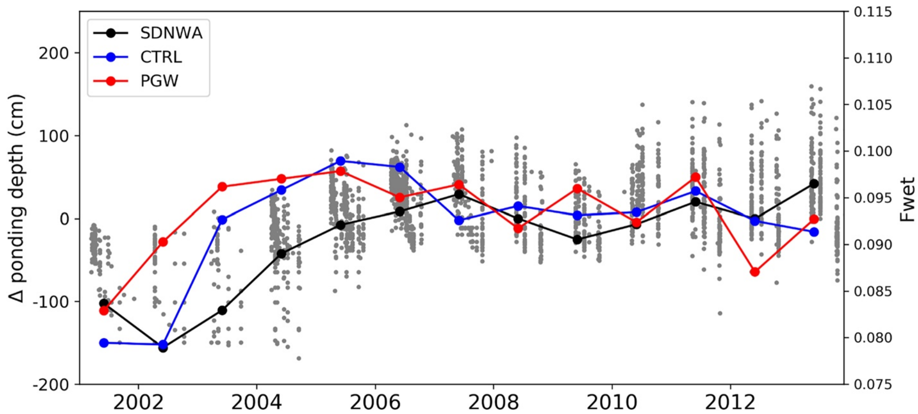

Figure 6. Scatter plot of Δ ponding depth (cm) (exact ponding depth−all-time mean depth) from 140 ponds in St. Denis National Wildlife Area (SDNWA) with annual F_{wet} value from the generalized additive model (gray dots). Records from April to September are shown. The black line is the mean Δ ponding depth averaged over 140 ponds for each year. The blue line is the mean F_{wet} value for each year from 2001 to 2013 and red line is for the corresponding period under the pseudo global warming (PGW) climate at the end of the 21st century. CTRL, control simulation.

the Canadian prairies. There is a clear gradient in the response of wetland fraction to SMC, with a weaker response in the moist southwest Manitoba uplands and aspen parkland compared with strong responses in drier regions including the western Alberta uplands, mid-boreal uplands, and fescue grassland.

In addition to the ecoregion-wise validation, we also compared the interannual F_{wet} change with the wetland ponding depth records at the SDNWA. Figure 6 shows the long-term ponding depth record from 140 ponds in the SDNWA (Δ ponding depth on the left axis) with annual F_{wet} values from CTRL and PGW in the corresponding 4-km grid cell (on right axis). Most of the SDNWA records are from April to September, so those same monthly F_{wet} values from the GAM are selected. Both ponding depth and F_{wet}reflect the moisture conditions in this area. From 2001 to 2013, an increasing trend of ponding depth and F_{wet} are evident. Additionally, although the SDNWA ponding depth is also affected by hydrological and ecological processes other than SMC, the general trend of SDNWA ponding depth largely agrees with that of CTRL F_{wet}. In 2001 and 2002, both data sets show values below the multi-year mean. An increasing trend of ponding depth and F_{wet} is obvious in the following years from 2003 to 2006, though the model predicts a stronger increase in F_{wet} in CTRL than the SDNWA ponding depth. For the rest of the time series from 2007 to 2013, both F_{wet} and ponding depth remain high with some interannual fluctuation. For the corresponding period in the PGW climate at the end of the century, the red line indicates a stronger increase in moisture conditions and larger interannual variations. This analysis adds credibility to our statistical model, demonstrating reasonable representation of interannual wetland variability in the Canadian prairies.

3.2. Change in Climate Conditions Between PGW and CTRL

Figure 7 shows the impacts of climate change (PGW-CTRL) on temperature (ΔT2, °C) and monthly precipitation (ΔPR in mm and %) and their average by ecoregion in four seasons in the Canadian prairies. All ecoregions exhibit a warming signal from 4 to 7°C, with the strongest warming in winter (DJF). The changes in precipitation vary across seasons and ecoregions, though mostly increase except in summer (JJA). In all seasons, the climate change scenario shows a negative correspondence between temperature warming and precipitation change. Ecoregion-wide, southwest Manitoba uplands experience the most warming in all seasons and usually the least precipitation increase, implying possible drying conditions in the eastern Canadian prairies. On the other hand, western Alberta uplands and fescue grassland receive the most precipitation increase and least temperature warming, indicating potentially wetter conditions in the western Canadian Prairies. These spatially heterogeneous changes in climatic conditions in future climate, in both temperature and precipitation, will manifest in altered hydrological conditions, that is, SM, and thus F_{wet} in the GAM.

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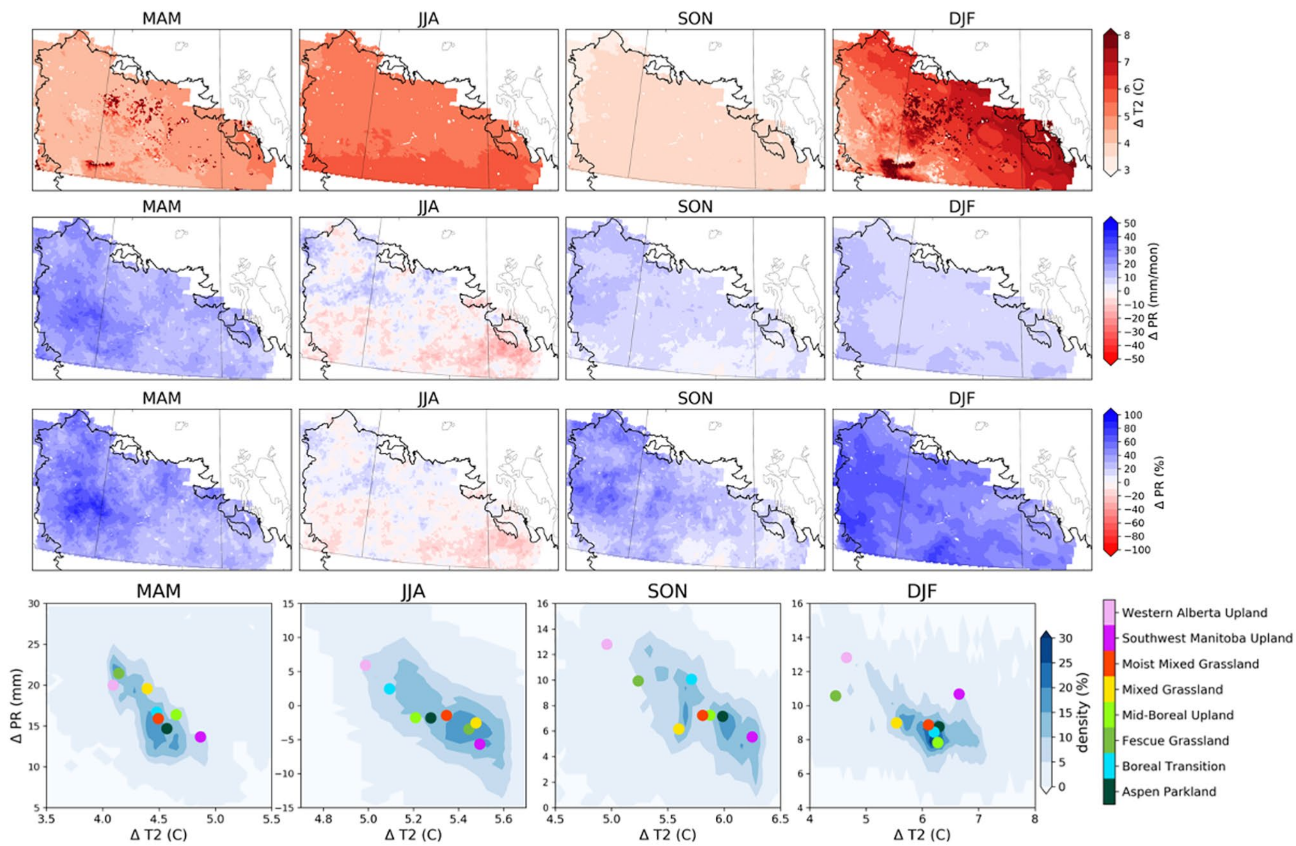

Figure 7. The first three rows show the pseudo global warming (PGW)-control simulation (CTRL) Δ change in 2-m temperature (ΔT2, °C), monthly precipitation $\left(\Delta\mathrm{PR}, \mathrm{mm} / \mathrm{mon}\right)$, and precipitation in %, in spring (MAM), summer (JJA), fall (SON), and winter (DJF). The fourth row shows the temperature change (ΔT2, °C) and precipitation change $\left(\Delta\mathrm{PR}, \mathrm{mm}\right)$ in the Canadian prairies by season and ecoregion. The blue shading represents the probability density for all the grid points in the study domain.

3.3. Spatially and Temporally Heterogeneous Water Balance and Wetland Changes

Climate change impacts on wetlands show strong spatial heterogeneity. Figure 8 presents the differences in F_{wet} (from March to August) between current and future climate as the relative change, calculated as ((F_{wet}_PGW-F_{wet}_CTRL)/F_{wet}_CTRL). For the area in the southwest mixed grassland ecoregion in Alberta and Saskatchewan, projected F_{wet} increases by about 30% (Figure 8a). In contrast, for the moist mixed grassland and mid-boreal uplands regions in southwest Manitoba and eastern Saskatchewan, which is a region with high F_{wet} under current climate (Figure 2), a decline in F_{wet} of about 20% is evident.

Changes in F_{wet} also demonstrate strong seasonal variation. Figures 8b and 8c show the changes in F_{wet} in spring and summer. In spring, there are extensive increases in F_{wet} in the southwest Canadian prairies.

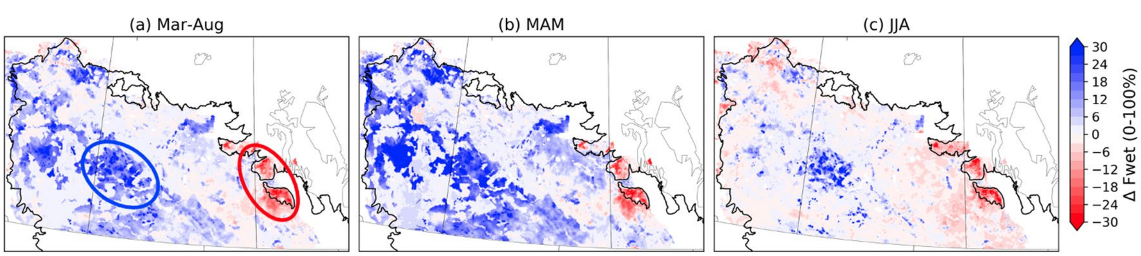

Figure 8. (a) Mean relative change in (F_{wet}_PGW-F_{wet}_CTRL)/F_{wet}_CTRL from March to August; (b) in spring (March to May; MAM) and (c) in summer (June to August; JJA). The blue and red circles in (a) highlight the areas of wetland gain in mixed grassland and loss in mid-boreal uplands ecoregions, respectively. CTRL, control simulation; PGW, pseudo global warming.

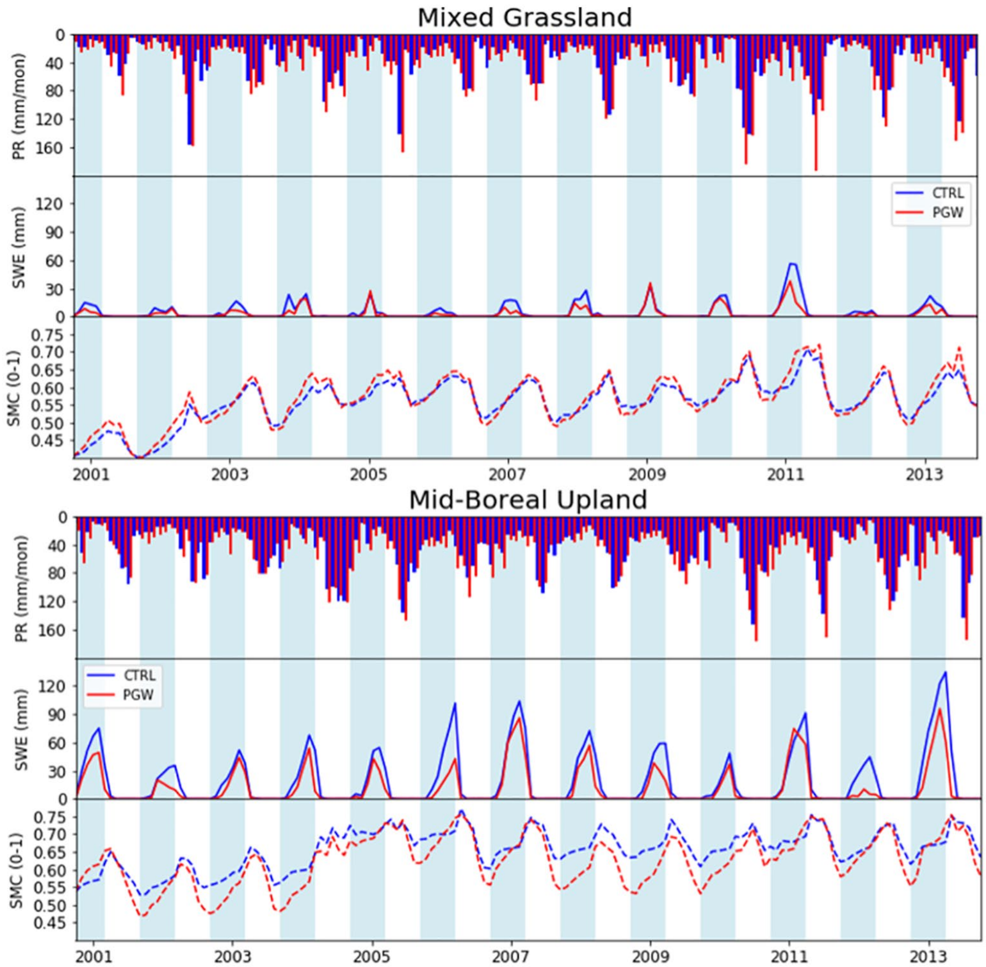

Figure 9. Hydrological cycle of precipitation (PR), snow water equivalent (SWE), and fractional soil moisture content (SMC) for two ecoregions highlighted in Figure 8, the mixed grassland and the mid-boreal upland. Blue and red lines represent the control simulation (CTRL) and pseudo global warming (PGW) climate scenarios, respectively. The light blue shaded blocks correspond to the period from September to February, and the white blocks from March to August.

In contrast, many areas in summer may see declining F_{wet}. This is due to both temperature warming and precipitation decline in the Canadian prairies in the future summer (Figure 6). As such, the southwest Canadian prairies are getting warmer and wetter with higher F_{wet} in future springs, while the mid-boreal uplands and moist mixed grassland in the eastern Canadian prairies will experience warmer and drier summers and reduced wetland extents. On the other hand, two regions show consistent change in F_{wet} in spring and summer (highlighted by blue and red circles in Figure 8a), corresponding to the mixed grassland and mid-boreal uplands ecoregions.

Figure 9 depicts the hydrological cycle of precipitation, SWE and SMC in the mixed grassland and mid-boreal uplands, the two ecoregions highlighted with increasing and decreasing F_{wet} in Figure 8a. In the mixed grassland, precipitation increases in almost all seasons, especially in the spring. However, the increased precipitation during cold seasons does not result in a greater snowpack due to warming winter temperatures. The combined effect of increased winter precipitation and temperature result in early melting of snow and higher SMC at the beginning of spring in PGW than CTRL. These wetter conditions in PGW can persist through spring and summer such that F_{wet} shows consistent increases in both spring and summer.

In the mid-boreal uplands, precipitation shows a strong decline in summer while still increasing in other seasons in Figure 9. Both late and slow accumulation, as well as early and rapid snowmelt, is revealed by the significant snowpack loss in this region. These conditions lead to higher infiltration, shown by the steeper

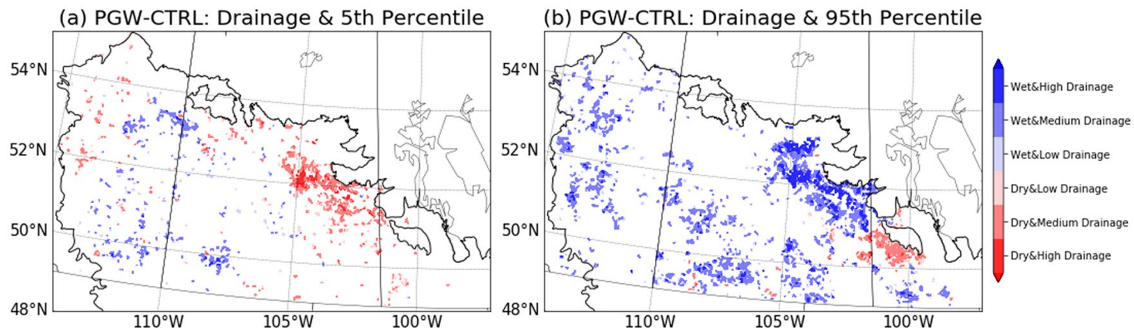

Figure 10. Combined effect of climate change and drainage under extreme (a) dry and (b) wet conditions. The dry and wet conditions are selected from the 5th and 95th percentile of the monthly wetland fraction results from control simulation (CTRL) and pseudo global warming (PGW) climate.

increase of SMC in PGW compared to CTRL in spring. On the other hand, hotter summers combined with reduced precipitation result in stronger ET demand, shown by the steeper SMC decline in the summer of PGW than in CTRL, characterizing a strengthened hydrological cycle in this region. Overall, the increase in precipitation in other seasons cannot compensate for the stronger ET demand in summer, thus, F_{wet} is smaller in PGW in both spring and summer.

Furthermore, for these two regions, it is recognized that SMC are shown to increase through winters. This could be due to intermittent warming during winter that causes snowmelt and infiltration into soil layers so that SM increase is even stronger in the PGW winters. A detailed water balance analysis is presented in the supporting information (Figure S6). As SMC is the key input for the GAM model, it is important to recognize this increase over winter. However, large-scale SM observations are required to validate this feature in the future.

3.4. Joint Impacts of Climate and Land-Use Change

The third objective of this study is to explore the joint effects of climate change and historical drainage on prairie wetlands and their ecosystem services. For this purpose, we combine the changes in F_{wet} under extreme dry/wet conditions induced by climate change and the drain score data in the Canadian prairies (Figure 2). Extreme dry conditions usually occur in summer months and the extreme wet conditions in spring months. Figure 10 shows the concordance of future climate change impacts ($\left|\Delta F_{wet}\right|$ greater than 0.1) and the drainage score under extreme wet and dry conditions (i.e., F_{wet}_PGW_95th-F_{wet}_CTRL_95th and F_{wet}_PGW_5th-F_{wet}_CTRL_5th, respectively). Although some areas are anticipated to be wetter even under the driest (5th percentile) conditions, parts of Saskatchewan with high drainage intensity may experience both amplified dryness and wetness. These combined impacts as well as their implications to conservation policies will be discussed in next section (Section 4.2).

4. Discussion

4.1. Climate Change Studies in the PPR

Several studies have projected climate change impacts on wetland densities in the PPR, ranging from local-scale (Johnson et al., 2005; G. Liu & Schwartz, 2012) to regional-scale (Garris et al., 2015; Niemuth et al., 2014; Sofaer et al., 2016). Variable study scales and data sources have made linking wetland spatial distribution and climatic conditions a challenge. The most common approach has been to statistically relate different climatic variables, landscape management types, and human footprints with wetland abundance (Garris et al., 2015; Herfindal et al., 2012; Niemuth et al., 2014; Sofaer et al., 2016). Typically, the key variable in these studies has been water balance (P-PET, Herfindal et al., 2015). Less often, physical process-based hydrology or LSMs have been applied in wetland studies (Capehart et al., 2011; Fan & Miguez-Macho, 2011; Johnson et al., 2005). These studies simulated hydroperiod, soil wetness, and shallow water table to represent the dynamics of wetlands in the PPR. Importantly, these variables are analogous to the surface water balance, as represented by the fractional SMC in this study.

Surface water distribution under climate change reflects the change in climate forcing and thus is subject to differences in study periods and regions, data sources, the choice of GCMs, whether and how the GCMs are downscaled, and hydrological models used. A recent ensemble of hydrological simulations showed that global drought severity, estimated by terrestrial water storage, could more than double the affected land area and population in the future (Pokhrel et al., 2021). Many parts of the Canadian prairies are currently experiencing relatively wet conditions, though our projections suggest that may change in some areas. Climate observation records show a wetting trend in precipitation, streamflow, SM and wetland pond counts in the southern PPR (McKenna et al., 2017; Niemuth et al., 2010) and eastern Canadian prairies (St. Jacques et al., 2014) since the 1990s. In the Smith Creek watershed, Dumanski et al. (2015) recorded an increasing trend and abnormally high values of streamflow volume, indicating that the watershed is already experiencing changes in the runoff mechanism, relying more on rainfall and less on snowmelt (Shook & Pomeroy, 2012). In our study, an increasing trend of F_{wet} index during the CTRL simulation period agrees with the above findings. However, in the PGW scenario, both warmer temperature and decreased summer precipitation contribute to reduced F_{wet} in the eastern Canadian prairies, especially in the mid-boreal uplands, boreal transition and eastern aspen parklands ecoregions. This projection differs from recent observations mainly due to reduced summer precipitation from the PGW scenario (Figure 4). This finding highlights the importance of precipitation projections in assessing hydrological and ecological impacts of regional climate change.

Climate change scenario and downscaling method selection greatly affects projections of hydrological responses and ecosystem impacts. Johnson et al. (2005) applied three climate change scenarios uniformly across the entire PPR and concluded that the region with greatest productivity in the central PPR will shift east- and southwards. However, these climate change scenarios are not realistic as GCM model projections are much more heterogeneous than a uniform increase of temperature or perturbations in precipitation for the entire PPR. Furthermore, St. Jacques et al. (2013) modeled the central Rocky Mountain river discharge (the western Canadian prairies in our study) using large-scale climate indices such as the Pacific Decadal Oscillation, El Nino Southern Oscillation and Arctic Oscillation/North Atlantic Oscillation, forced with CMIP3 until 2096 and predicted declining surface water availability. Climate model downscaling studies using the delta method in the Canadian Rockies (Cline River watershed, Kienzle et al., 2012; Beaver Creek watershed, Forbes et al., 2011; North Saskatchewan River watershed, MacDonald et al., 2012) also project a change in seasonality of the hydrological regime in this region: earlier onset of snowmelt and higher peak streamflow in spring but lower streamflow in summer. This strong seasonal contrast of wetter spring and drier summer is consistent with our predictions. However, we predict greater summer precipitation compared to the above studies, highlighting the differences in projection scenarios, especially with respect to precipitation. Finally, another recent modeling study, using the same PGW method in the Marmot Creek Basin in the western Canadian prairies, also demonstrated declining and earlier melting of snowpack, inducing huge increases in streamflow (236%) in spring and reductions in summer (12%), and an overall increase of 18% annually (Fang & Pomeroy, 2020).

The main limitation of the PGW method is the trade-off between selection of climate scenarios, simulation time and high model resolution. With high-resolution convection-permitting configuration, these simulations require great computational resources, which limits the selection of climate change scenarios and the simulation time period. For example, only one emission scenario (RCP8.5) from an ensemble of 19 GCM members and shorter simulation time (13 years) is used in this study, compared to the delta method, which allows exploration of climate change impacts on longer simulation periods or for more emissions scenarios. Nonetheless, the PGW method with high-resolution is currently considered the best option to assess future climate changes and their impacts on hydrology and ecology for large regions (Li et al., 2019; C. Liu et al., 2017; Prein et al., 2016) for a specific scenario.

We also recognize the limitations of Equation 6 used in the GAM. In Equation 6, the variation in SMC is assumed to represent the hydrological responses to climate change and the ecoregion factors are treated as constants. In this approach, critical hydrological processes at local and watershed scales, such as blowing snow redistribution and intermittent runoff, are underrepresented in our model. These processes, which occur at sub-grid resolution (Shaw et al., 2012), are not sufficiently monitored over large regional scales in the Canadian prairies, nor are they represented at the typical scale of LSMs. Although Noah-MP does not directly simulate blowing snow, it reasonably simulates snow accumulation and snowmelt, as demonstrated against gridded distributed snow observation (see Figure S3). One recent study applied the Cold Region Hydrological Model in the Mauvais Coulee Basin and demonstrated that spatiotemporal variation in snow redistribution and sublimation can be significant for surface water balance, though requires fine-scale field observations to verify (Van Hoy et al., 2020). We are actively developing a dynamic surface water storage scheme in the Noah-MP LSM, incorporating inflow, outflow, and ET feedback from wetlands to the atmosphere. On the other hand, ecoregion boundaries were held constant to allow us to attribute the changes of F_{wet} solely to SMC, driven by two sets of climate forcings from the current and future climate. Furthermore, incorporating climate-driven changes to ecoregion boundaries or characteristics into the modeling framework is outside the scope of this study.

4.2. Implications for Wetland Conservation

The spatial heterogeneity of climate change impacts on wetland extent in the Canadian prairies is challenging for conservation decision-makers, especially under extreme climate conditions and uncertainties associated with anthropogenic drainage. Considering extreme climate conditions (droughts and floods; Figure 10) can constrain the magnitude of possible wetland area change, complementing an assessment of effects of climate change on average wetland conditions (Figure 7). Including anthropogenic drainage can help spatially prioritize conservation efforts by revealing both areas that may remain robust to climate change and areas where wetland ecosystem services may be imperiled by climate change and drainage.

Projected changes in F_{wet} suggest the need for a diversified approach to wetland conservation, one that considers both the future hydrological suitability of wetland retention and restoration efforts, as well as how historical drainage patterns will interact with changes in wetland extent to affect the availability of wetland ecosystem services. For example, in Figure 10, the consistent wetland increase in the western PPR, under both wet and dry extremes, suggests wetland retention and restoration will be hydrologically favorable under climate change, with water available to fill wetlands and maintain wildlife habitats even in relatively dry summers. Relatively wet areas may act as refuges for mobile wetland-associated species like waterfowl, as long as upland conditions (i.e., sufficient perennial cover for nesting) are favorable. In contrast, highly drained areas in eastern Saskatchewan will be challenged under fluctuating hydrological conditions. The combination of high wetland loss and intensified drought conditions under climate change will mean a shortage of wildlife habitat in dry years. In contrast, extreme wet conditions may lead to flooding in spring snowmelt season, exacerbated by wetland loss. Therefore, conserving and restoring wetlands in the aspen parkland, mid-boreal uplands, and boreal transition regions in eastern Saskatchewan may act as a buffer against flooding during intensified future wet periods. Other areas of the Canadian prairies, like western Manitoba, could become challenged by moisture deficits (even in the wettest years) that will not favor the inundation and persistence of wetlands. Conservation planning will benefit from the incorporation of future wetland distributions for multiple applications such as refining spatial targeting (e.g., by the PHJV for waterfowl habitat), targeting wetland restorations to maximize ecosystem services, and more.

In addition to impacting wetlands via change in the surface water balance, climate change may have indirect effects on wetlands via land-use change. Wetland conservation strategies should take into account these direct and indirect climate effects. For example, Beaman (2016) found that climate change may alter agricultural economics such that annual-seeded crops increase at the expense of natural and semi-natural land covers. Given that drainage for agriculture has been the historical driver of wetland loss on the prairies (Doherty et al., 2018; Watmough & Schmoll, 2007), with ongoing losses of ∼3% of wetland area per decade, land-use change could augment or offset direct climate effects on wetlands (PHJV, 2014). Previous research combining modeling the direct effects of climate change with changes in land use in the US portion of the PPR suggested that projected changes in land use are not expected to greatly modify the direct effects of climate change (Sofaer et al., 2016). However, the Canadian PPR may exhibit different patterns and this should be investigated.

5. Conclusions

Conservation of prairie wetlands is crucial to protect the vital services they provide including regulating floods, improving water quality, and supporting biodiversity. It is necessary to consider the impacts of climate change in conservation planning, for they pose a threat to wetland habitats through alteration of the hydrological cycle. The approach used in this study, a dynamical downscaling from a high-resolution convection-permitting regional climate simulation as our climate projection, provides better representation of land surface properties and less uncertainty in the precipitation forecast than many previous efforts to model the effects of climate change in the PPR. It is also more realistic and informative than using GCM-scale uniform climate forcings to simulate hydrological responses in this region.

Overall, the climatic change is projected to be wetter in all seasons, except in summer, with strong spatial heterogeneity and seasonal variation and corresponding effects on wetlands. For the western Canadian prairies, in particular in the mixed grassland ecoregion in Saskatchewan, wetland fraction is expected to increase in future climate in both the spring and summer seasons. Increased precipitation with warmer temperatures over winter results in higher late accumulation and early melting of snow. This is manifested in a substantial increase in SM in future springs when compared with the current climate. However, in the eastern Canadian prairies, wetlands are expected to increase in spring but decrease in summer, due to reduced summer precipitation and intensified ET in this region. Moreover, this precipitation reduction and stronger ET lead to declining wetland fraction in both spring and summer for the mid-boreal uplands along the northeast boundary of the Canadian prairies.

The heterogeneous change in projected climatic and hydrological conditions may alter the current wetland distribution of the Canadian prairies, where wetlands are more abundant in the east. This has important implications for wetland conservation and ecosystem services, especially when considered in light of historical wetland losses due to anthropogenic drainage. Areas expected to experience extended summer drying coinciding with areas with high density of drainage ditches (and thus already high wetland loss) may be challenged through loss of wetland ecosystem services. The western PPR, with moisture conditions conducive to wetland persistence through the spring and summer, will remain a safe choice for wetland conservation efforts. Assessments of the effects of climate change on wetland conservation must fully consider ecological, economic, and social realities along with the potential for climate-induced changes to determine the most effective spatial targeting of wetland conservation and restoration.

Data Availability Statement

The WRF simulation over the contiguous United States (C. Liu et al., 2017) can be accessed at https://rda.ucar.edu/datasets/ds612.0/TS1 (last access: August 2020). The Noah-MP GW model is driven by the NCAR high-resolution land data assimilation system (Chen et al., 2007) and can be downloaded from https://github.com/NCAR/hrldas-release/. The Noah-MP LSM can be accessed from https://github.com/NCAR/noahmp. The Noah-MP GW simulation data for the Prairie Pothole Region in this study can be accessed in the public repository: https://osf.io/jea9y/?view_only=3acdbc3c43b943aea9e949f7fa7dd592. The Canadian Wetland Inventory data are not publicly available due to agreements signed with government partners. Data are available to researchers with appropriate credentials who sign a data sharing agreement. Contact information can be found at https://maps.ducks.ca/cwi/. Drain score data are copyright of Her Majesty the Queen in Right of Canada, In Press 2014, reproduced with the permission of the Government of Canada and are not publicly available due to government policy.

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