Coupled and Stand-alone Regional Climate Modeling of Intensive Storms in Western Canada

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Abstract

A coupled atmospheric-hydrologic system models the complex interactions between the land surface and the atmospheric boundary layer, and the water-energy cycle from groundwater across the land surface to the top of the atmosphere. A regional climate model called WRF (Weather Research Forecasting) was coupled with a land surface scheme (Noah) to simulate intensive storms in central Alberta, Canada. Accounting for the land-atmosphere feedback enhances the predictability of the fine-tuned WRF-Noah system. Soil moisture, vegetation, and land surface temperature influence latent and sensible heat fluxes, and modulate both thermal and dynamical characteristics of land and lower atmosphere. WRF was set up in a two-way, three-domain nested framework so that the output of the outermost domain (D1) was used to run the second domain (D2) and the output of D2 was used to run the innermost domain (D3). In two-way nesting, D3 and D2 provide the feedback to their outer domains (D2 and D1), respectively. D3 was set at a 3-km resolution adequate to simulate convective storms. WRF-Noah was forced with climate outputs from Global Climate Models (GCMs) for the baseline period 1980–2005. A quantile-quantile bias correction method and a regional frequency analysis were applied to develop intensity-duration-frequency (IDF) curves from precipitation simulated by WRF-Noah. The simulated baseline precipitation of central Alberta agreed well with observed rain gauge data of Edmonton. The 5^{th}-generation NCAR mesoscale atmospheric model (MM5) was also set up in a 3-domain, but one-way nesting configuration. As expected, after bias correction, precipitation simulated by MM5 was less accurate than that simulated by WRF-Noah. For storms of short durations and return periods of more than 25 years, both MM5 driven by SRES climate scenarios of CMIP3 and WRF-Noah driven by RCP climate scenarios of CMIP5 projected storm intensities in central Alberta to increase from the base period to the 2050s, and to the 2080s.

Key Words

Regional climate models, WRF and MM5, stand-alone and coupled modes, land surface scheme, dynamic downscaling, intensive storms, Alberta, Climate Change.

Introduction

As the Earth warms, higher temperatures likely mean that more precipitation will fall over shorter time intervals, thus increasing the frequency and severity of extreme storm events. In other words, global warming could modify existing engineering design tools, such as Intensity-Duration-Frequency (IDF) curves, of municipalities across North America. For example, in recent years Canada has experienced severe storms which resulted in billions of dollars of flood damages, such as the flood events of Calgary and Toronto in 2013 which, as the respective worst natural disaster of Alberta and Ontario, are also ranked the first and the third largest natural insured disasters in Canada, respectively (Milrad et al., 2015). In the 2013 flood of Calgary, over 10,000 basements of the City were flooded, 100,000 people were evacuated, and the cost of damage was estimated to exceed 5 billion dollars. Central Alberta had also experienced severe storms in the early 21st Century, which, according to the Canadian Disaster Database (www.publicsafety.gc.ca/cnt/rsrcs/cndn-dsstr-dtbs/indexeng.aspx), had resulted in considerable damage. According to the current design standard of Edmonton, the 1995, 2004 and 2012 severe flood events in the City were supposed to be floods of 100 to 200-year return period. However, they had been occurring about once every 10 years, which clearly demonstrates that the current design criteria for Edmonton are obsolete because its current infrastructure design practice does not reflect the effect of climate change on the intensive storms in Alberta.

The prediction skill of hydro-meteorological models has significantly improved in recent decades. Advances in both climate and hydrologic models, and the availability of more powerful and efficient computing resources facilitate the development of more complex systems based on the combination of spatially distributed physically-based hydrologic models with deterministic atmospheric forecasting systems. Coupled atmospheric-hydrologic modeling aims at describing the full atmospheric-terrestrial regional water cycle, i.e. extending from the top of the atmosphere, through the boundary layer, via the land surface and subsurface till lateral flow in the groundwater and in the river beds. Fully two-way coupled model systems thereby give the possibility to study long range feedbacks between groundwater, soil moisture redistribution, and precipitation. By accounting for the land-atmosphere feedbacks, improved process descriptions and coupled atmosphere-hydrologic models may also increase the performance of hydrometeorological predictions for various spatial and temporal scales. The objective of this study was therefore to compare the performance of a stand-alone regional climate model (RCM) with a coupled RCM in modeling intensive storms in Western Canada over historical and future periods.

1. Regional Climate Modeling System

The atmospheric grid resolutions of most global climate models (GCMs) range from slightly less than 1^{o} to about 3^{o} (e.g., https://portal.enes.org/data/enes-model-data/cmip5/resolution), e.g., the resolution of ACCESS 1-3 is 1.25^{o} x 1.875^{o}, which are too coarse for basin-scale hydrologic studies. Therefore, simulations of GCMs on historical climate and climatic responses to changing atmospheric compositions should be downscaled statistically or dynamically by regional climate models (RCMs), translating them to a finer spatial scale that is more meaningful in the context of local and regional impacts, such as the hydrologic impact of climate change to river basins, e.g., Guyennon et al. (2013). RCMs can be set up in a stand alone or a coupled mode with a land surface model (LSM). In this study, we modeled the intensive storms in Alberta of Western Canada, using a coupled and stand-alone regional climate modeling system.

1.1 Stand-alone MM5 System

Kuo et al. (2015) adopted a one-way nesting (Figure 1), 3-domain configuration for MM5 driven by ECMWF's ERA-Interim reanalysis data as the initial and 6-hourly lateral boundary conditions for the outermost domain (D1) of 27-km resolution with 76 grids in the latitude and 90 grids in the longitude directions (Figure 2). The D1 output was used to run the second domain (D2) of 9-km resolution, which was used to run the innermost domain (D3) of 3-km resolution located in central Alberta. All the three domains were run with 23 vertical sigma (r) levels at 0.995 to 0.025., which is defined as $\frac{p0\_pt}{pso\_pt}$, where *p0* is the reference-state pressure, *pt* is the model top pressure assigned as 100 hPa in this study, and *ps0* is the reference-state surface pressure. Kuo et al. (2015) found that after 6 hours of model simulation, there was no major shift in the simulated temperature, precipitable water and 10-m wind fields, which suggested that a 6-h spin up was sufficient, and so model outputs in the initial 6-hour simulations were discarded as spin-up data. MM5 was run for 27 May–August periods (4-month) between 1984 and 2010.

MM5 was set up with the high-resolution, Blackadar planetary boundary layer (PBL) scheme, the mixed-phase (Reisner et al., 1998) explicit moisture scheme, five-layer soil model, and the rapid and accurate radiative transfer model longwave radiation scheme (RRTM; Mlawer et al., 1997). Given the 27-km spatial resolution of D1 is not sufficient to resolve the small-scale convective precipitation events, the Kain–Fritsch 2 (Kain, 2004) cumulus parameterization (CP) was applied in the D3 domain. The CP option in D2 was turned off to avoid over-simulating precipitation and to remove instability in D2 as a compromised solution in order to simulate more accurate MJJA storms in D3, and to provide better initial and boundary conditions for D3. At 3-km, MM5 can credibly simulate the climate system without CP (Erfani et al., 2003).

1.2 Land Atmosphere Feedback

The land surface and atmosphere feedback is important for regional climate modeling. Not accounting for this feedback may induce simulation errors in heat and water fluxes that affect humidity, temperature, air pressure, precipitation, deep convection, etc. Previous studies have revealed that soil moisture has a positive feedback on precipitation in North America's summer (Kanamitsu and Mo, 2003). Soil moisture, vegetation, and land surface temperature influence latent and sensible heat fluxes which can affect air temperature, boundary layer stability, and precipitation. When soil moisture is limiting, more energy will be used for sensible heat flux than for latent heat flux, consequently the near surface temperature increases. Therefore, via energy fluxes, soil moisture and temperature modulate both thermal and dynamical characteristics of land surface and lower atmosphere. Further feedbacks may occur through changes in cloud cover, albedo, radiation, and atmospheric circulations; thermal circulations can be induced by non-uniform vegetation cover (Hong et al., 1995); air temperature can vary by several ^{o}C spatially by local variations in land-surface fluxes even under homogeneous grassland.

Seneviratne et al. (2006) found that the contribution of land-atmosphere coupling can be up to 2/3 of the total summer variance over the transitional zone in European climate. Zhang et al. (2008) also found strong coupling between soil moisture and daily mean temperature in Great Plains, USA. Using satellite and ground observed data, observed soil moisture data in Nebraska, Mahmood et al. (2012) found that soil moisture at the top 10 and 25 cm were associated with precipitation and maximum temperature, which demonstrated land-surface-atmosphere interactions, which were also controlled by vegetation dynamics, evapotranspiration, and snow and ice dynamics. From coupling several land surface models (LSMs) with WRF (Weather Research and Forecasting) (Skamarock et al. 2008), a regional climate model (RCM), Jin et al. (2010) showed that the accuracy of temperature simulations had improved. Lorenz et al. (2012) also found that their LSM reduced the bias of climate variability and extremes simulated by an RCM. In other words, incorporating land-atmosphere feedback could enhance the predictability of an RCM simulating convective storms partly because the interaction of energy and moisture fluxes near the surface would be accounted for.

For the past several decades, studies have shown that land surface processes can play a significant role in mesoscale atmospheric processes, so researchers have developed and tested different LSMs since the first simple LSM developed by Manabe (1969). Over the years LSM has grown in complexities to now the 3rd generation LSMs. Past studies conducted to explore the impact of land surface characteristics on climate were such as the sensitivity of climate to land surface albedo, roughness, soil holding capacity, roots, and vegetation. Land-atmosphere feedback plays a key role in the climate of arid and semi-arid regions. To account for land-atmosphere feedback, WRF is coupled with some LSMs to simulate the future climate of central Alberta. Coupled mode simulation is computationally much more intensive and more prone to numerical instability. Also, due to differences in the grid size between RCM and LSM, a scheme linking the two components is often necessary (Kerkhoven and Gan, 2006). Many LSMs have been designed to model sub-grid heterogeneity of land surface biophysical and hydrological processes, and to account for the influence of sub-grid variability on the exchange of water and energy fluxes in the soil-vegetation-atmosphere continuum. Representative 2nd generation LSMs are built upon the ideas of a `force-restore`, 2-layer soil, and a single canopy layer that can dynamically model energy and mass transfers between land and atmosphere, such as Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson et al., 1986), Simple Biosphere scheme (SiB) (Sellers et al., 1986), Noah (Ek et al., 2003), Interactions Soil-Biosphere-Atmosphere (ISBA) (Noilhan and Planton, 1989), MISBA (Kerkhoven and Gan, 2006), Variable Infiltration Capacity (VIC) (Liang et al., 1994), and CLASS, a Canadian LSM (Verseghy, 2009), etc.

A later version of CLASS has more soil thermal and moisture layers and a separate treatment of vegetation canopy. CLASS has been coupled to a hydrologic model, WATFLOOD (Soulis et al., 2000), called WATCLASS, which extends the water movement from only vertical direction to both vertical and horizontal directions. MESH is a newer version of WATCLASS developed by Environment Canada. Coupling RCM and LSM has been useful for studying the interactions between the atmosphere, biosphere, and hydrosphere (Koster et al. 2004). Small (2001) used the coupled MM5-OSU (Oregon State University, a land surface model), to examine the influence of soil moisture anomalies on North American Monsoon (NAM) precipitation variability. Vivoni et al. (2009) found the influence of initial soil moisture on the rainfall generation of the NAM by WRF. Using the National Centers for Environmental Prediction (NCEP) Regional Spectral Model (RSM) coupled with OSU, Kanamitsu and Mo (2003) found that the effect of soil moisture was more pronounced than evaporation on the summertime precipitation over Arizona and New Mexico. By coupling the Community Land Model (CLM) with an RCM (RegCM), Steiner et al. (2009) demonstrated interactions between land cover and the West African monsoon. Based on Flux Network data, the coupling of RegCM and the Integrated Biosphere Simulator (IBIS) improved the simulation of latent heat flux over USA. Amin et al. (2017) modeled the interactions between land surface and atmosphere to assess the climate change impact on Muda and Dungun regions of Malaysia using the Watershed Environmental Hydrology Model (WEHY) and MM5. MM5 was used to dynamically downscale climate projections of 15 GCMs for the study sites, which was coupled with WEHY to investigate the climate change impact on the flood conditions of these two regions. Results showed a rising trend in the frequency of flood in these regions in the late 21 century.

1.3 WRF-Noah Coupled System

Kuo et al. (2021) coupled WRF, the next version of MM5, to a land surface scheme (LSM) called Noah to account for the land-atmosphere feedback in simulating the future storms of central Alberta (Figure 1). WRF is a new non-hydrostatic atmospheric model originally based on the MM5 model. Several studies have compared the performance between WRF and MM5 (Wilmot et al. 2014, Gilliam and Pleim, 2010, Awan et al, 2011, Gsella et al., 2014). The choice of physical parameterization is sensitive in both models, but WRF is more sensitive than MM5 (Awan et al, 2011). Gsella et al. (2014) found that the performance of both models was of similar quality, but WRF was better in reproducing the annual average of precipitation and relative humidity. In general, the consensus is that WRF outperforms MM5 (Gilliam and Pleim, 2010, Steenveld et al., 2010). The WRF-Noah coupled system was driven by the RCP (Representative Concentration Pathways) climate scenarios (RCP2.6, RCP4.5, and RCP8.5) of selected GCMs of Intergovernmental Panel of Climate Change (IPCC, 2013) to project future Intensity Duration Frequency (IDF) curves of central Alberta under climate change impact.

In fine tuning the configurations of WRF so that it will simulate representative regional climate of central Alberta and western Canada, we conducted sensitivity tests on short wave (SW) radiation, long wave (LW) radiation, microphysics (MP), and cumulus parameterization (CP) schemes (Kuo et al., 2021). We found that LW radiation simulated was insensitive to the LW radiation scheme selected. Both CAM and RRTMG SW radiation schemes estimated similar incoming SW radiations. However, the CAM scheme produced a more accurate representation of the 2-m air temperature. From sensitivity tests conducted on MP parameterizations, the WRF Double Moment 6-class scheme was selected because its simulations had the most neutral bias in precipitation and 2-m air temperature. The CP schemes tested generally over-simulated precipitation, but they did not seem to influence the simulation of most other climate variables. From various test runs, the final schemes of WRF chosen were the Kain-Fritsch cumulus scheme (Kain 2004), WRF Double-Moment 6-class Microphysics scheme, CAM Longwave (LW) and Shortwave (SW) radiation scheme, NOAH land surface scheme (LSM) (Ek and Mahrt 1991), and the Yonsei University planetary boundary layer (PBL) scheme, respectively. These configurations simulated representative climate of central Alberta (Kuo et al., 2021) and the Mackenzie River basin (Kuo et al., 2020). By accounting for the land-atmosphere interaction and feedback, the predictability of WRF in simulating convective storms was enhanced, while simulation errors in heat and water fluxes, which could affect humidity, temperature, and precipitation, reduced. Soil moisture, vegetation and land surface temperature influence latent and sensible heat fluxes, which in turn affect air temperature and precipitation. When soil moisture is limited, more energy will be used for sensible heat flux than for latent heat flux, resulting in higher near-surface temperature. Therefore, soil moisture and temperature modulate both thermal and dynamical characteristics of land and lower atmosphere. Similar to the MM5 (Figure 2), WRF was also set up in a two-way, three-domain nested framework so that the output of the outermost domain (D1) was used to run the second domain (D2) and the output of D2 was, in turn, used to run the 3-km resolution, innermost domain (D3). However, at two-way nesting, the inner domains (D3 and D2) provide the feedback to their outer domains (D2 and D1), respectively. By the 3-domain framework, D3 was set with a spatial resolution adequate to simulate convective storms (3-km). WRF was forced with climate outputs from GCMs for the baseline period 1980–2005. A quantile-quantile bias correction method and a regional frequency analysis were applied to precipitation simulated by WRF (Figure 3). The baseline regional climate of central Alberta and MRB simulated by WRF agreed well with gridded observed climate data of Environment Canada.

The interactions between land surface and atmosphere are based on the exchange of latent and sensible heat fluxes, short and longwave radiation as well as momentum. In order to interactively couple LSM with WRF, at each time step WRF provides LSM with all relevant climate parameters such as precipitation, net long and short wave radiation, humidity, and wind speed. Then the LSM calculates the latent heat flux, sensible heat flux, and momentum flux. These fluxes are returned to WRF where they provide the lower boundary condition for WRF's lowest level for the next time step. WRF and LSM exchange fluxes through a subroutine call from WRF to LSM.

The annual maximum precipitation intensities simulated by WRF-Noah was first bias corrected which was necessary because of errors coming from data, modeling, scales, parameterization, etc. After bias correction, future IDF curves were estimated (Figure 3).

2. Discussions of Results

We compared observed precipitation from 13 rain gauges (RG) in Edmonton, Canada, for 1985-2005 and precipitation simulated by the stand-alone MM5 and the coupled WRF-Noah systems. The upper, median, and lower (U,M,L) bounds of model simulations of WRF for Edmonton in central Alberta generally matched the 13 RG data considerably better than that of the stand-alone MM5 which tended to over-simulate the 1985-2005 observed precipitation in Edmonton (Figure 4). Comparing the bounds of IDF curves of 2, 25 and 100 year return periods for Edmonton over 1984-2010 derived from the rain gauge data, precipitation simulated by MM5 and the coupled WRF-LSM systems, it was again obvious that the U and L bounds of IDF curves developed from WRF's simulations for Edmonton generally matched the 13 RG data considerably better than the IDF curves developed from MM5's simulations which tended to over-simulate the 1985-2005 observed precipitation in Edmonton (Figure 5). IDF curves developed from the

NARCAAP (North American Regional Climate Change Assessment Program) data set show that the NARCAAP data (Mearns et al. 2009) under-simulated the intensities of storms of 3 to 24-hr duration of Edmonton.

This is what we have expected given both land surface and land-atmosphere feedback processes can play a significant role in mesoscale atmospheric processes as explained in Section 2.2. Not accounting for this land-atmosphere feedback may induce simulation errors in heat and water fluxes that affect humidity, temperature, air pressure, precipitation, deep convection, etc. as reflected in the discrepancies between the precipitation simulated by MM5 and the observed RG data of Edmonton. By accounting for the land surface and land-atmosphere feedback processes, the precipitation simulated by WRF-Noah is clearly better than that of MM5 even though both systems are set up with the same 3-domain framework, D1 to D3 of the same spatial resolutions of 27, 9 and 3 kms, respectively.

3.1 Comparing future (2041–2100) IDF curves projected by WRF-Noah and MM5

[It will be desirable to compute risk of the occurrence of an extreme rainfall of a give duration and the compute the change in risk due to projected increases in rainfall. This is what people in practice want.]

The present (1984–2015) IDF curves of 50-year return period for Edmonton wee compared with IDF curves projected for the 2050s (2041–2070) and the 2080s (2071–2100) derived from simulations of WRF driven with RCP climate scenarios of IPCC (2013), respectively (Figure 6). Apparently, more intensive storms are projected to occur in the future, especially for storms of short durations (≤ 1-h). The projected lower bound of IDF curves in the 2050s (solid lines) have higher intensities than those of the present (1984–2015) IDF curves (shaded grey) for short durations of storms of all return periods. The projected upper bound of IDF curves in the 2050s have higher intensities than the present (1984–2015) IDF curves (shaded grey) for all durations of storms of all return periods (only IDF curves of the 50-year return period is shown in Figure 6). For storms of durations longer than 1-h, the projected IDF curves (both upper and lower bounds) of the 2050s overlap with the present IDF curves. However, overlapped areas between the projected and the present IDF curves for storms of longer durations are small compared to non-overlapped areas. Overall, the highest projected increase in storm intensities are generally of about 15-min duration, with a maximum increase of 143.1 %, a median increase of 47.9 %, and a minimum change of -8.7 % among all return periods (not shown in Figure 6). The maximum, median, and minimum percentage changes were derived from eight sets of RCP projections. As expected, the projected IDF curves for the 2080s generally exhibit higher intensities than those of the 2050s. Overall, storm intensities of central Alberta are projected to increase from 2050s to 2080s for storms of short durations and return periods of more than 25 years.

From regional IDF curves of Edmonton derived from future MJJA precipitation of central Alberta simulated by MM5 in a one-way, 3-domain nested framework, Kuo et al. (2015) demonstrated that return periods of future short-duration storms simulated by MM5 driven by three SRES (Special Report on Emission Scenarios) climate change scenarios (A2, A1B, and B1) of IPCC (2007), for three 30-year periods (2011-2040, 2041-2070, 2071-2100), are expected to decrease. MM5 was forced with climate scenarios of four GCMs of CMIP3 (Phase 3 of the Coupled Model Inter-comparison Project), CGCM3 (Canadian GCM), ECHAM5 (German GCM), CCSM3 (Community Climate Systems Model of USA), and MIROC3.2 (Japanese GCM, Model for Interdisciplinary Research on Climate). At relatively fine resolutions (27 to 3 km resolutions), MM5 can simulate the regional climate process more accurately than coarse resolution GCMs. However, these results are based on the simulations of MM5 operating at a stand-alone mode. As a whole, the projected changes of Kuo et al. (2015) are relatively modest compared to the projected changes of WRF driven by RCP climate scenarios in the future IDF curves of central Alberta in the 2050s and the 2080s, particularly regarding projected maximum changes (%) (Figure 6). There are several reasons behind the difference in results between Kuo et al. (2015) and this study.

First, SRES of IPCC (2007) had relied on research processes based on limited exchanges of information among physical, biological, and social scientists (Moss et al., 2010). The implications of climate change will depend not only on the Earth system's responses to changes in radiative forcing, but also on how human and society respond to changes in economies, technology, fossil fuel consumptions, lifestyle, and policy. On the other hand, Representative Concentration Pathways (RCP) of IPCC (2013) were developed from a new process toward the goal of integrating socioeconomic development and scientific advances, such as improved representation of the terrestrial carbon cycle in climate and integrated assessment models. Developing RCP climate scenarios began from identifying radiative forcing characteristics that support modelling a wide range of plausible future climates in response to possible changes in economies, technology, fossil fuel consumptions, lifestyle, and policy (Moss et al., 2010). RCPs were selected to provide needed inputs of emissions, concentrations, and land use/cover for climate models.

Second, SRES, A2, A1B, and B1 of four GCMs of IPCC (2007) for central Alberta were downscaled using MM5, which is the fifth-generation, mesoscale atmospheric model of National Center for Atmospheric Research, NCAR/Penn State University (Hanrahan et al., 2015). In contrast, WRF is a new non-hydrostatic atmospheric model originally based on the MM5 model. WRF is also more widely used besides research purposes (Wilmot et al. 2014). Several studies have compared the performance between WRF and MM5 (Wilmot et al. 2014, Gilliam and Pleim, 2010, Awan et al, 2011, Kusaka et al, 2005, Gsella et al., 2014). The choice of physical parameterization is sensitive in both models, but WRF is more sensitive than MM5

(Awan et al, 2011). Gsella et al. (2014) found that the performance of both models is of similar quality, but WRF is better in reproducing the annual average of precipitation and relative humidity. In general, the consensus is that WRF outperforms MM5 (Gilliam and Pleim, 2010, Hanna et al., 2010, Steenveld et al., 2010). Moreover, WRF is coupled to a land surface scheme to account for land-atmosphere feedback, while MM5 is set up in a stand-alone mode. While we do not know how the climate will evolve over the 21st Century under the impacts of global warming and other environmental changes, results of WRF-Noah should be more representative than that of the stand alone MM5. In general, predicting the potential impact of climate change decades away involve many possible uncertainties such as data errors and limitations of RCMs such as WRF and MM5 - which are simplified versions of nature - especially when running MM5 at a stand-alone model that ignores the effects of land surface processes and land-atmosphere feedback.

3.2 **Risk Analysis**

At the annual time scale, assuming independent events, the risk of failure (*R*) is the probability that a *T*-year return period event will occur at least once in n years,

$$R = 1 - \left(1 - \frac{1}{T}\right)^n \quad (1)$$

Based on Equation (1), the risk of encountering at least one 100-year flood in a 5-year period is 0.049, and the corresponding risk in a 20-year period will increase to 0.182, which means *R* is expected to increase by 0.133 if a project life span is increased from a 5-year to a 20-year periods. In Figure 5, the upper bound of 1-hour storms of 25-year (100-year) return period simulated by MM5 have an estimated intensity of about 53 mm/hr (90mm/hr), while the corresponding intensities of the upper bound of 1-hour storms of similar return periods simulated by WRF-Noah are about 20 mm/hr (50 mm/hr), which are considerably lower. This means that the stand-alone MM5 climate model tends to over-simulate the intensity of storms compared to the coupled, WRF-Noah model (see Figure 4). In other words, for short duration storms of central Alberta, the risk of failure (*R*) based on the simulations of MM5 is expected to be considerably higher than that based on the simulations of WRF-Noah. In the above example, for a project of 20-year life span (n), the estimated risk of encountering at least one or more 1-hour storm of intensity equal to or higher than 50mm/hr based on the simulations of MM5 will be about 0.56 [$=1 - (1- 1/25)^{20}$] while that based on WRF-Noah is only about 0.182 [$=1 - (1 - 1/100)^{20}$], which clearly demonstrates the advantage of modeling the intensive storms in Western Canada using a coupled over a stand-alone RCMs. Comparing figures 5 and 6, upper and lower bounds of projected IDF curves of 50-year return period for the 2050s and 2080s derived from RCP 4.5 and 8.5 climate scenarios of four GCMs downscaled by MM5 and WRF-Noah respectively shows a projected increase in the intensity of projected storms, especially storms of short durations. Based on the IDF curves, the upper bound of the intensity of 1-hour storms simulated by WRF-Noah over 1984-2010 of 100-year return period (Figure 5) is about 50mm/hour, while that of the 2050s and 2080s simulated by WRF-Noah of 50-year return period (Figure 6) is about 55 mm/hour and 60 mm/hour, respectively. This means the risk of damage *R* is projected to be higher, from about 0.182 for a project life of 20 years over 1984-2010 to higher than 0.33 [$=1 - (1 - 1/50)^{20}$] in 2050s, and even higher in 2080s.

3. Summary and Conclusions

A coupled atmosphere-hydrological system models the complex interactions between the land surface and the atmospheric boundary layer, and the water-energy cycle from groundwater across the land surface to the top of the atmosphere. A regional climate model called WRF (Weather Research Forecasting) is coupled to a land surface scheme called Noah to investigate intensive storms of central Alberta, Canada. From various test runs, the schemes of WRF chosen are the Kain-Fritsch cumulus scheme, WRF Double-Moment 6-class Microphysics scheme, CAM Longwave (LW) and Shortwave (SW) radiation scheme, and the Yonsei University planetary boundary layer (PBL) scheme. These configurations simulated representative climate of central Alberta. By accounting for the land-atmosphere interaction and feedback, the predictability of WRF in simulating convective storms is enhanced while simulation errors in heat and water fluxes - which affect humidity, temperature, and precipitation - is reduced. Soil moisture, vegetation, and land surface temperature influence latent and sensible heat fluxes, which, in turn, affect the air temperature and precipitation. When soil moisture is limited, more energy will be used for sensible heat flux than latent heat flux, resulting in higher near-surface temperature. Therefore, soil moisture and temperature modulate both thermal and dynamical characteristics of land and lower atmosphere.

WRF was set up in a two-way, three-domain nested framework so that the output of the outermost domain (D1) was used to run the second domain (D2) and output of D2 was, in turn, used to run the 3-km resolution, innermost domain (D3). In two-way nesting, the inner domains (D3 and D2) provide the feedback to their outer domains (D2 and D1), respectively. By the 3-domain framework, D3 is set with a spatial resolution adequate to simulate convective storms. WRF is forced with climate outputs from Global Climate Models (GCMs) for the baseline period 1980–2005. A quantile-quantile bias correction method and a regional frequency analysis were applied to precipitation simulated by WRF. The baseline regional climate of central Alberta and MRB simulated by WRF agrees well with 13 rain gauge data from Edmonton, Alberta.

The 5th-generation NCAR mesoscale atmospheric model (MM5) in a stand-alone mode was also set up in the same three-domain, but only one-way nesting configuration. For the outermost domain D1, the Kain-Fritsch 2 cumulus parameterization was used, assuming that a 27-km grid spacing is too coarse to resolve smaller scale rainfall explicitly. For all three domains, the high-resolution Blackadar PBL scheme was used, along with the mixed-phase explicit moisture scheme, the rapid and accurate radiative transfer model longwave radiation scheme, and the Five-Layer Soil model surface scheme. After bias correction, precipitation generated by MM5 is less accurate than that simulated by the WRF-Noah coupled system. An examination of moisture advection during individual over-simulation cases suggests that MM5 may not properly handle the redistribution of moisture in regions of complex terrain. Both MM5 driven by SRES climate scenarios of CMIP3 and WRF-Noah driven by RCP climate scenarios of CMIP5 projected storm intensities in central Alberta to increase from the base period (1984-2010) to the 2050s, and to the 2080s for storms of short durations and return periods of more than 25 years. The future risk of exceeding the design storms of certain periods over the life span of projects in central Alberta is expected to increase.

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Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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