Influence of Open Water Bodies on the Modeling of Summertime Convection over the Canadian Prairies

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(Manuscript received 18 November 2015, in final form 14 July 2016)

ABSTRACT

There are numerous water features on the Canadian landscapes that are not monitored. Specifically, there are water bodies over the prairies and Canadian shield regions of North America that are ephemeral in nature and could have a significant influence on convective storm generation and local weather patterns through turbulent exchanges of sensible and latent heat between the land and the atmosphere. In this study a series of numerical experiments is performed with Environment and Climate Change Canada’s Global Environmental Multiscale (GEM) model at 2.5-km grid spacing to examine the sensitivity of the atmospheric boundary layer and the resulting precipitation to the presence of open water bodies. Operationally, the land–water fraction in GEM is specified by means of static geophysical databases that do not change with time. Uncertainty is introduced in this study into this land–water fraction and the sensitivity of the resulting precipitation is quantified for a convective precipitation event occurring over the Canadian Prairies in the summer of 2014. The results indicate that with an increase in open water bodies, accumulated precipitation, peak precipitation amounts, and intensities decrease. Moreover, shifts are seen in times of peak for both precipitation amounts and intensities, in the order of increasing wetness. Additionally, with an increase in open water bodies, convective available potential energy decreases and convective inhibition increases, indicating suppression of forcing for convective precipitation.

1. Introduction

The effects of land surface processes on prestorm convective environment has been documented in previous studies (e.g., Eltahir 1998; Findell and Eltahir 2003a,b; Capehart et al. 2011). Additional studies have explored the role of vegetation and soil moisture conditions in land–atmosphere interactions (Cook et al. 2006; Entekhabi et al. 1992). In these studies small-scale land surface features were ignored or neglected in comparison to the larger ecosystem, even though they may play an important role in the land–atmosphere interactions. One such feature is the prairie wetland complex of the northern Great Plains, including the Canadian Prairies region (Fang et al. 2007; Shook and Pomeroy, 2012).

These wetlands are the result of glacial activity when the retreating continental ice sheet left behind depressions formed by uneven deposition of glacial sediments. These depressions collect local runoff, creating wetlands referred to as “sloughs” or “prairie potholes” (La Baugh et al. 1998; Pomeroy et al. 2005). Because of a lack of integration of these wetlands with external drainage systems, these wetlands form closed basins that connect to each other when subjected to very wet conditions (Pomeroy et al. 2010). The distribution of water in these wetlands is governed by several processes, such as precipitation, evapotranspiration, snowmelt runoff, groundwater dynamics, and antecedent conditions of soil and depressional storage (Fang and Pomeroy 2008; van der Kamp and Hayashi 2009).

The Canadian Prairies region is marked by complex and varied hydrology. Approximately one-third of annual precipitation occurs as snowfall and the resulting spring snowmelt produces 80% or more of annual local surface runoff (Gray and Landine 1988; Dumanski et al. 2015). The highest amount of rainfall occurs from May to early July. The governing factors for most rainfall events occurring during spring and early summer over the prairies are large frontal systems. The most intense
short-duration rainfall events occurring in summer are related to local-scale convective storms (Pomeroy et al. 2005; Raddatz and Hanesiak 2008; Shook and Pomeroy 2012). During summer, most of the rainfall is consumed by evapotranspiration and surface runoff occurs only during intense rainfall events, thereby resulting in negative water balance of the wetlands. In winters, soil freezing occurs up to a depth of 1 m and water from snowmelt determines the water balance of wetlands (van der Kamp et al. 2003). Several studies (Johnson et al. 2005; Kundzewicz et al. 2007; Covich et al. 1997) have found that these wetlands are susceptible to climate change impacts and land-use changes in the surrounding regions. According to MEA (2005), warming climate not balanced by an increase in precipitation could reduce wetland areas, thereby affecting the benefits they provide, such as improvement of water quality, recharging aquifers, and carbon management.

The regional hydrology and climate of the Canadian Prairies are greatly influenced by the spatial and temporal variability of these wetlands. Several studies have investigated the mechanisms controlling the soil moisture–precipitation feedbacks (Betts et al. 1996; Skamarock et al. 2008; Taylor 2015). To understand these feedbacks via a modification of boundary layer characteristics, Findell and Eltahir (2003a,b) performed a study in the eastern limits of the northern Great Plains and found that high surface moisture can have negative and positive responses on convective precipitation. In another study done over the Alpine region in Europe, Hohenegger et al. (2009) attempted to investigate soil moisture–precipitation feedbacks using explicit and parameterized convection. The study found significant differences in the simulated soil moisture–precipitation feedbacks between two low-resolution modeling frameworks characterized by different cloud convection schemes.

In all the aforementioned studies, open surface water extent of the considered region was represented in the form of soil moisture. The present study examines the role of open water bodies and their impacts on the storm environment of a summertime convective event using Environment and Climate Change Canada’s (ECCC) Global Environmental Multiscale (GEM) model at 2.5-km grid spacing. Operationally, open water bodies are incorporated into GEM in the form of land–water fraction (LWF), which indicates the percentage of the grid covered by land and is obtained using static geophysical databases. The summertime convective event selected for this work occurred in the Canadian Prairies region of southern Saskatchewan on 3–4 June 2014. For this event, a 24-h simulation beginning at 0600 UTC 3 June 2014 is executed using estimated and perturbed values of LWF. To our knowledge, no studies have dealt with the sensitivity of atmospheric boundary layer and resulting convective precipitation to open water bodies, where the latter were represented as land–water fraction. Also, the application of a kilometer-scale atmospheric model for such a study is a novel aspect of this work.

2. Model

a. Model description

The GEM 2.5-km model used in this work is very similar in configuration to the model that is currently used at the Meteorological Service of Canada (MSC) for operational short-range regional forecasting. This model is characterized by a horizontal grid spacing of approximately 2.5 km (GEM2.5), an integration time step of 60 s, and 58 terrain-following vertical levels up to 10 hPa.

Two limited-area computational grids, with a 2.5-km grid (Fig. 1, red box) nested within a 10-km grid (Fig. 1, black box), are set up over the study area (Fig. 1, blue box). The simulations begin at 0600 UTC 3 June and continue up to 0600 UTC 4 June 2014. Outputs from ECCC’s 10-km operational RegionalDeterministic Prediction System (RDPS; Mailhot et al. 2006) provide the hourly lateral boundary and initial conditions to the 10-km GEM limited-area model (LAM). Surface variables are initialized using MSC’s 10-km sequential Land Data Assimilation System where soil moisture and soil temperature increments are related to differences between observed and predicted screen-level air temperature and relative humidity (Bélaire et al. 2003a).

At the kilometer scale, a detailed microphysics scheme from Milbrandt and Yau (2005) is used to
represent clouds and precipitation. This scheme is based on a double moment solution for six different hydrometeor types and has been used at MSC operations for several years (Mailhot et al. 2010). On the other hand, no representation of deep convection is activated at this scale, whereas the effect of shallow convection is still considered with a Kuo Transient scheme (Bélair et al. 2005). Other aspects of the model physics include the atmospheric radiation, based on a correlated-\(k\) distribution approach described in Li and Barker (2005), and the boundary layer turbulent mixing performed with a turbulent kinetic energy scheme (Benoit et al. 1989; Bélair et al. 1999).

Surface processes over land are based on the Interactions between Soil, Biosphere, and Atmosphere (ISBA) scheme (Noilhan and Planton 1989; Bélair et al. 2003a,b). This scheme solves the force–restore equations for surface temperature and soil moisture (two levels for each variable) and provides the lower boundary conditions to GEM’s vertical diffusion schemes, also interpreted as surface fluxes of heat, water, and momentum. The effect of vegetation on the albedo, the roughness, and on the evaporation is also considered in ISBA. Initial conditions for ISBA’s prognostic variables (i.e., surface temperatures and soil moisture) are provided by MSC’s operational Land Data Assimilation System (Bélair et al. 2003a), in which screen-level observations of air temperature and relative humidity are assimilated. Evaporation over open water surfaces is simply calculated as potential evaporation dependent on the water surface temperature and surface-layer turbulent exchanges.

Finally, surface characteristics related to orography, vegetation and soil characteristics, land-sea mask, and surface roughness length fields are produced using a geophysical processor software (Mailhot et al. 2010; Carrera et al. 2010) combining information from several different databases. Vegetation characteristics and orographic information are derived from a global U.S. Geological Survey (USGS) database. Soil texture information over the Canadian Prairies is provided by combining information based on databases from the U.S. Department of Agriculture (USDA) database and Agriculture and Agri-Food Canada (AAFC), with a database from the Food and Agriculture Organization of the United Nations (FAO) filling in the remaining gaps.

b. Case review

A summertime convective event over the Canadian Prairies region of southern Saskatchewan on 3–4 June 2014 was selected for this work. Such an event is controlled by local factors where surface heating occurs during the day initiating convection in the afternoon toward sunset along large-scale surface boundaries, with little or no contribution from prior convection. These factors enable surface processes (sensible and latent heat and fluxes) to have a significant effect on convection.

The motivation behind examining a single case is to allow an optimal impact of the surface water fraction uncertainty on precipitation, that is, a summertime case with large solar insolation and net radiation at the surface, with slow-moving afternoon convective precipitation more closely related to surface fluxes than to large-scale forcing.

Figure 2a shows sea level pressure and surface air temperature derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim; Dee et al. 2011) at 1800 UTC 3 Jun 2014. The storm area (blue box in Fig. 1) is located in a broad area of lower pressure extending northwest from a low pressure center over northeastern Colorado. The low pressure system has well-defined warm and cold fronts.
Figure 2b summarizes the large-scale forcing over the region of interest at 1800 UTC 3 June 2014. Shown is the 700-hPa geopotential height along with the quasigeostrophic–omega (i.e., QG–$\omega$) values, calculated from the QG–$\omega$ equation [Bluestein 1992, see his Eq. (5.6.11)], using ERA-Interim. As Davies (2015) points out, QG–$\omega$ has a diagnostic value in providing a quantitative estimate of the vertical velocity field, which can be seen as a good approximation to the vertical velocity field on the synoptic scale (Durran and Snellman 1987). The units of $\omega$ are pascals per second, with negative (positive) values denoting regions of diagnosed ascent (descent). At 700 hPa there is a broad trough extending from northwest to southeast across the central prairies, as an upper-level ridge moves eastward. Over southern Saskatchewan, there is diagnosed weak large-scale ascent, much weaker when compared to the frontal region to the southeast. Quantitatively, the $\omega$ values are on the order of $-0.15 \text{ Pa s}^{-1}$ ($-1.5 \text{ cm s}^{-1}$).

Satellite and radar imagery are important tools for detecting signatures associated with convective precipitation. Figure 3 shows Geostationary Operational Environmental Satellite (GOES) infrared images over Canada at 1500, 1800, and 2100 UTC 3 June and at 0000 and 0300 UTC 4 June 2014. As the event progresses, the temperature of the cloud tops over the region of occurrence changes from gray ($\sim 23^\circ C$) at 1500 UTC 3 June to white ($\sim -58^\circ C$) at 0000 UTC 4 June 2014, indicative of cold cloud tops and convective conditions. Figure 4 shows radar images from the Bethune radar near Regina depicting precipitation rate and intensity at 0010, 0110, and 0210 UTC 4 June 2014. Radar reflectivities higher than 50 dBZ persisted between 0010 and 0210 UTC, indicating organized convection (Callado and Pascual 2005).

3. Experimental setup

For the above-described event, a 24-h simulation commencing at 0600 UTC 3 June 2014 is performed using two different land–water masks, one based on a database from Natural Resources Canada (NRC) called CanVec (CN) and the other from the Globcover (GC; an initiative of European Space Agency) databases, with GC acting as the control case. CN is a digital cartographical reference obtained primarily from the National Topographic Data Base, the GeoBase initiative, and the data update using Landsat 7 or SPOT imagery coverage (ftp.geogratis.gc.ca/pub/nrcan_rncan/vector/canvec/doc/Read_me.txt). The GC land-cover product includes a 300-m global land-cover map resulting from an automated classification of Medium Resolution Imaging Spectrometer Instrument (MERIS) Fine Resolution (FR) time series (Bontemps et al. 2011). In CN and GC, open water bodies are expressed in the form of LWF. Figure 5 shows the spatial distribution of LWF over the region of occurrence. It can be seen that LWF shows discontinuities along the U.S.–Canada border. For the CN database, a large proportion of this discontinuity could be attributed to the fact that since CN is only available
over Canada, the U.S. region was covered using the GC database. Additionally, since aerial surveys are used to derive LWF, more discontinuity is added to already ephemeral data. **Figure 5** shows that GC has a greater percentage of land than CN. The same is supported by **Fig. 6**, which shows boxplots of the percentage of land covered with water, referred to as open water extent (OWE), such that

![Radar images from the Canadian Historical Weather Radar](image)

**FIG. 5.** LWF derived from (a) CN, (b) GC, and perturbed (c) $\beta = 5$ and (d) $\beta = 10$ wetland scenarios over the region of interest of convective precipitation (southern Saskatchewan, shown by the blue box in **Fig. 1**).
The area covered by these boxplots corresponds to the region of occurrence of the selected convective event (Fig. 1, blue box), hereafter referred to as the storm region. The red line denotes the median, the asterisk markers indicate the mean, and the plus signs indicate the outliers. The length of the box indicates the interquartile range or the variability, with the variability proportional to the length. These boxplots indicate that the CN database shows more open water bodies than GC and thus a wetter situation as compared to the drier GC. Additionally, the OWE values given by CN are more variable than those given by GC, which could be attributed to the differences in the corresponding underlying algorithm, resolution, and data sources. The overall magnitude of the differences between GC and CN represents a level of uncertainty that is exploited in our LWF perturbation methodology.

To evaluate the sensitivity of GEM2.5 forecasts, two perturbation scenarios are defined by using the inherent differences between GC and CN in the following manner:

\[ x = \text{LWF}_{\text{CN}} - \beta \left[ \max(0, \text{LWF}_{\text{GC}} - \text{LWF}_{\text{CN}}) \right] \]  

(1)

\[ \text{LWF}_{\text{new}} = \max \left( x, \frac{\text{LWF}_{\text{CN}}}{2} \right) \]  

(2)

(3)

where

\[ \beta = 5, 10. \]

Table 1 summarizes the four wetland scenario experiments along with the corresponding values of OWE and LWF. The CN database is selected for perturbation as it shows greater OWE (indicated by higher OWE values). The idea behind this is to select a subset of LWF values that preserves an approximation of the original distribution of LWF. One way of accomplishing this is by breaking down the LWF values (corresponding to CN) into five bins (quintiles). The highest two quintiles (60th–80th and 80th–100th percentiles) are defined as

<table>
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<tr>
<th>Scenario</th>
<th>OWE</th>
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<tr>
<td>CN</td>
<td>0.04</td>
</tr>
<tr>
<td>GC</td>
<td>0.02</td>
</tr>
<tr>
<td>( \beta = 5 )</td>
<td>0.15</td>
</tr>
<tr>
<td>( \beta = 10 )</td>
<td>0.23</td>
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</table>
the “maximum land” category. The third (40th–60th percentile) and second quintiles (20th–40th percentile) are defined as the “moderate land” category, and the “minimum land” category is assigned to the lowest quintile (0th–20th percentile). The mean LWF values given by GC and CN are found in the moderate land category. Besides these two scenarios, two more wetland scenarios are selected whose mean LWF values lie in the lowest quintile range (0th–20th percentile), thereby representing minimum land and hence “maximum wetland conditions.” These scenarios correspond to $\beta = 5$ and $\beta = 10$. From Figs. 5 and 6, it can be seen that the former (i.e., $\beta = 5$ and $\beta = 10$) have more OWE than the CN and GC. The mean of OWE corresponding to CN, GC, $\beta = 10$, and $\beta = 5$ are 22%, 23%, 27%, and 25%, respectively.

4. Results

This section compares the precipitation amounts, intensities and magnitude, and times of peak precipitation occurrence obtained from GEM2.5 simulations using the four wetland scenarios shown in Table 1.

a. Precipitation amount

The spatial distribution of 24-h cumulative precipitation (mm) for the four considered wetland scenarios is shown in Fig. 7. It can be seen that for all scenarios, GEM2.5 is able to generate precipitation for this specific case. The spatial distribution of cumulative precipitation becomes less dispersed or more spatially concentrated as OWE increases. This is primarily due to the greater spatial coverage of precipitation in the range 5–20 mm, corresponding to GC and CN, in comparison to $\beta = 5$ and $\beta = 10$. In this range, the percentage of cells corresponding to CN, GC, $\beta = 10$, and $\beta = 5$ are 29%, 30%, 25%, and 21%, respectively.

The percentage of grid cells lying in other categories of precipitation amounts are shown in Fig. 8. For each scenario, the highest number of grid cells (≈60%–70%) fall in the low precipitation amounts (<5 mm) range, whereas the least number of cells (<3%) are in the highest precipitation amounts (>50 mm) range. For amounts lying in the range 20–50 mm, the perturbed runs exhibit greater percentage of cells than both the GC and CN scenarios. In this range, the percentage of cells corresponding to CN, GC, $\beta = 10$, and $\beta = 5$ are 22%, 23%, 27%, and 25%, respectively.

b. Precipitation intensity

Histograms showing the spatial distribution of precipitation rates (RT) for the entire event can be seen in Fig. 9. Rates corresponding to GC and CN are consistently higher than the perturbed ones. In each class, $\beta = 5$ has a higher number cases than $\beta = 10$, except for the range 22–28 mm h$^{-1}$, where the two are comparable. The temporal distribution of mean RT for the entire event at 15-min time steps starting from 1800 UTC 3 June 2014 is shown in Fig. 10. Mean RT values begin to increase steeply at 0100 UTC 4 June 2014. The differences between the wetland scenarios are more pronounced between 0100 and 0500 UTC 4 June 2014.
c. Magnitude and occurrence of peaks

The magnitude and occurrence of peak precipitation amounts and intensities are likely to contribute to significant uncertainties in precipitation forecasts when compared to the corresponding mean values. Table 2 shows peak precipitation (PCP) and time of maximum PCP obtained for each wetland scenario. The simulation corresponding to GC exhibits the highest peak (0.34 mm), followed by CN (0.31 mm), $\beta = 5$ (0.29 mm), and $\beta = 10$ (0.25 mm). For the perturbed simulations, the time of peak is delayed by an hour. As observed for PCP, peak RT values (Table 3) also decrease with an increase in OWE. Peak RT for CN, GC, $\beta = 5$, and $\beta = 10$ are 1.35, 1.26, 1.21, and 1.02 mm h$^{-1}$, respectively. In comparison to CN and GC, the time of

![Fig. 8. Percentage of grid cells in the storm region lying in different precipitation ranges.](https://journals.ametsoc.org/doi/abs/10.1175/JHM-D-15-0225.1)

![Fig. 9. Histogram showing the distribution of RT (mm h$^{-1}$) for the entire event for CN, GC, $\beta = 5$, and $\beta = 10$ over the storm region.](https://journals.ametsoc.org/doi/abs/10.1175/JHM-D-15-0225.1)
maximum RT shows a delay of an hour for $\beta = 5$ and 45 min for $\beta = 10$.

d. Atmospheric stability indices

The convective available potential energy (CAPE) and convective inhibition (CIN) play important roles in convective precipitation (e.g., Markowski et al. 2002; Brooks et al. 2003). CAPE is the amount of energy available to a parcel as it rises vertically through the atmosphere. Since CAPE characterizes the positive buoyancy of an air parcel, it is regarded as an indicator of atmospheric instability and is therefore valuable in predicting the occurrence of severe weather. CIN indicates the amount of energy that must be supplied to a parcel for it to rise from the surface to the level of free convection. Therefore, the higher the CIN, the smaller is the likelihood of developing convection.

Figure 11 shows the predicted CAPE and CIN values beginning at 1200 UTC 3 June 2014 from the four wetland experiments. It can be seen that with an increase in OWE, there is a decrease (increase) in the CAPE (CIN) values. Decreasing CAPE suggests that any deep convection that develops will become less intense as open water bodies increase in value. Increasing CIN indicates that the initiation becomes more difficult with an increase in wetness. Therefore, the environment in the perturbed runs ($\beta = 5$ and $\beta = 10$) becomes less favorable for convective development than the control runs (CN and GC). These results are consistent with the observed decrease in precipitation amounts (Table 2) and spatial variability of precipitation (Fig. 7), with an increase in OWE.

5. Conclusions

The current study attempts to understand the sensitivity of the atmospheric forecasts to the presence of open water bodies through a series of numerical experiments using the GEM atmospheric model at 2.5-km grid spacing. In current GEM versions, open water bodies are expressed in the form of LWF derived from static geophysical databases (CN and GC). These LWF values were perturbed and the sensitivity of the resulting precipitation amounts and intensities was quantified for a summertime convective precipitation over the Canadian Prairies (southern Saskatchewan) occurring on 3–4 June 2014. The novelty of this work lies in the manner of representation of open water bodies in the form of OWE and the application of GEM at 2.5-km grid spacing for the sensitivity study presented in this work.

The results indicate that an increase in OWE has an effect on the nature of the precipitation event. With an increase in OWE, mean PCP and RT have shown a

<table>
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<tr>
<th>Wetland scenarios</th>
<th>GC</th>
<th>CN</th>
<th>$\beta = 5$</th>
<th>$\beta = 10$</th>
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</thead>
<tbody>
<tr>
<td>Peak (mm)</td>
<td>0.34</td>
<td>0.31</td>
<td>0.29</td>
<td>0.25</td>
</tr>
<tr>
<td>Time of peak (UTC)</td>
<td>0230</td>
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<td>Peak (mm h$^{-1}$)</td>
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<td>1.26</td>
<td>1.21</td>
<td>1.02</td>
</tr>
<tr>
<td>Time of peak (UTC)</td>
<td>0245</td>
<td>0245</td>
<td>0345</td>
<td>0330</td>
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</table>
decrease. Additionally, with an increase in the areal coverage of open water bodies, peak PCP and RT have also shown a decrease in magnitude and shift (delay) in timing. The spatial structure of 24-h cumulative precipitation became more organized (i.e., more spatially concentrated) with increasing OWE. The decrease in CAPE and increase in CIN (with an increase in OWE) has been reflected in the resulting precipitation fields in which the control cases (CN and GC) have greater cumulative precipitation, peak PCP, RT, and time of peak for the four wetland scenarios: CanVec (CN), Globcover (GC), \( \beta = 5 \), and \( \beta = 10 \), than the perturbed cases.

Precipitation is a highly variable field, and explicitly defining the underlying processes is a challenge since most of them operate at a scale smaller than the grid spacings of weather prediction models. With reference to the current study, it is likely that increasing the horizontal resolution of GEM may influence the resulting precipitation fields and modify the sensitivities found. Hence, one of the extensions of this work could be to explore the influence of open water bodies on atmospheric boundary layer using different versions of GEM (in terms of reduced grid spacing and inclusion of processes operating at finer scales).

Acknowledgments. The authors thank the three anonymous reviewers for their helpful and insightful comments which have led to an improved manuscript. Ron McTaggart-Cowan is thanked for his help with the QG–omega calculations shown in Fig. 2. This research was funded by a Government Related Initiatives Program (GRIP) of the Canadian Space Agency (project 13MOA07102).

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