UNIVERSITÉ DU QUÉBEC À MONTRÉAL

LES IMPACTS BIOPHYSIQUES DES CHANGEMENTS DE L'UTILISATION DES TERRES EN AMÉRIQUE DU NORD AVEC LE MODÈLE RÉGIONAL DU CLIMAT CANADIEN

MÉMOIRE

PRÉSENTÉ

COMME EXIGENCE PARTIELLE

DE LA MAÎTRISE EN SCIENCES DE L'ATMOSPHÈRE

PAR

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MARS 2016

UNIVERSITÉ DU QUÉBEC À MONTRÉAL
Service des bibliothèques

Avertissement

REMERCIEMENTS

Je tiens à remercier ma directrice de recherche Laxmi Sushama et mon co-superviseur Hugo Beltrami pour leur soutien.

Pour leur soutien inconditionnel, je tiens à remercier ma famille qui ont représenté un pilier fondamental à mon développement mental et professionnel.

Je remercie aussi Melissa Cholette, Dominic Matte, Marilys Clement, Carolyne Pickler et Gregory Yang pour leur aide dans la traduction des séminaires et du mémoire. Je voudrais également remercier tous mes camarades de la promotion 2012, sans eux je aurrais pas surmonter la barrière linguistique.

Je tiens à remercier à Katja Winger et Luis Duarte pour leur assistance technique en ce qui concerne les simulations MRCC. Oleksandr Huziy et Camille Garnaud pour leur aide dans le traitement des ensembles de données et Gulilat Tefera Diro pour son soutien et ses commentaires.

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LISTE DES ABRÉVIATIONS, SIGLES ET ACRONYMES

ARC   Advanced Research Computing

BU-MODIS   Boston University's Moderate Resolution Imaging Spectrometer (US)

CH_4 Méthane

                 Methane

CIP   Calcul Informatique de Pointe

CLASS   Canadian Land Surface Scheme, version 3.5 (Canada)

CO_2 Dioxyde de Carbone

                 Carbon dioxide

CRCM5   Canadian Regional Climate Model, version 5 (UQAM, Canada)

CRCM5_LUC   CRCM5 simulation using potential vegetation dataset

CRCM5_PV   CRCM5 simulation using the vegetation that has presence of LUC

CREATE   Training Program in Climate Sciences

ECMWF   European Centre Medium-Range Weather Forecasts (Europe)

ERA-40   Second generation reanalysis of ECMWF

ERA-Interim   Third generation reanalysis of ECMWF

ESCER	Centre pour l'Étude et la Simulation du Climat à l'Échelle Régional
GCM	Global Climate Model
GEM	Global Environmental Multiscale model developed by the Canadian Meteorological Centre (CMC, Canada)
LAI	Leaf Area Index
LHF	Latent Heat Flux
LUC	Land Use Change
MCG	Modèle climatique global
MRCC5	Modèle régional canadien du climat, cinquième version (UQAM, Canada)
N	North
NSERC-DG	Natural Sciences and Engineering Research Council of Canada Discovery Grant
NWP	Numerical Weather Prediction
SHF	Sensible Heat Flux
SPOT	Satellite Pour l'Observation de la Terre
T2M	Two meter temperature
TMax	Maximum Temperature
TMin	Minimum Temperature

UQAM	Université du Québec à Montréal
US	United States
W	West

LISTE DES SYMBOLES

cm	Centimeter
kg/m^2	Kilogram per meter square
km	Kilometer
km^2	Kilomètre carré
	Kilometer square
m	Meter
mm/day	Millimeter per day
mm/month	Millimeter per month
W/m2	Watt per square meter
°C	Degrees Celsius
°	Degrees of latitude and longuitude
%	Pourcentage
	Percentage

RÉSUMÉ

Les changements dans l'utilisation des terres sont des manifestations évidentes de l'activité humaine de par le changement de la végétation naturelle par des terres cultivées. Cela modifie les caractéristiques biophysiques de la région et affecte le climat local. Ce projet a pour but d'étudier les impacts des effets biophysiques des changements dans l'utilisation des terres sur le climat régional en Amérique du Nord.

La cinquième génération du Modèle Régional Canadien du Climat (MRCC5) a été utilisé afin de comparer deux simulations utilisant différents ensembles de données de la couverture terrestre. Le premier ensemble de données représente la végétation terrestre sans activité humaine de par l'absence de terres cultivées (végétation potentielle) et le deuxième ensemble est l'utilisation actuelle des terres correspondant à la fusion de la végétation potentielle et de terres cultivées. Dans la simulation utilisant le deuxième ensemble de données, les forêts et les prairies sont remplacées par des terres cultivées dans les régions centre-ouest des Etats-Unis et centre-sud du Canada. Par conséquent, les caractéristiques de surface, comme la couverture fractionnaire de végétation, l'indice de surface foliaire, l'albédo, la longueur de rugosité et la profondeur des racines, sont différentes de la simulation utilisant le premier ensemble de données. Les deux simulations couvrent la période de 1988-2012 et les conditions aux frontières latérales sont fournies par les réanalyses ERA-Interim. La couverture de glace et la température de surface de la mer sont également données par ERA-Interim.

La comparaison des deux simulations suggère des valeurs d'albédo plus élevées en hiver sur les régions où il y a des changements dans l'utilisation des terres. L'absence de cultures en hiver conduit à une rétroaction positive avec la neige. Ces valeurs plus élevées d'albédo se reflètent dans des valeurs plus basses de la température à 2 mètres. Certaines régions, comme l'est des Etats-Unis, montrent également un refroidissement en été pour la simulation avec changements dans l'utilisation des terres en raison de flux de chaleur latente plus élevés et de flux de chaleur sensible plus basse. Les cycles annuels de certaines variables d'intérêts ont été analysés pour deux régions où les changements dans l'utilisation des terres sont manifestes, à savoir le centre-sud du Canada et le centre-nord des États-Unis. L'analyse des cycles saisonniers suggère que l'effet de refroidissement dû aux changements dans l'utilisation des terres est présent durant toute l'année. Les impacts des changements dans l'utilisation des terres sur l'évapotranspiration, l'humidité du sol et les précipitations sont également présents tout au long du cycle annuel. Cependant, les

impacts des changements dans l'utilisation des terres sur les eaux de ruissellement se limitent essentiellement à la saison de la fonte des neiges.

Cette étude a permis de fournir des informations utiles concernant les impacts des changements dans l'utilisation des terres sur le climat et l'hydrologie de l'Amérique du Nord.

Mots clés: impacts biophysiques, changements dans l'utilisation des terres, modélisation régionale du climat, Amérique du Nord

CHAPITRE I

INTRODUCTION

À travers le temps, le climat et l'environnement de notre planète ont été fortement modifiés par les activités humaines [Mahmood et al., 2010]. Ces modifications se reflètent entre autres. Dans l'évolution des ressources en eau, dans les émissions de gaz traces dans l'atmosphère et dans les changements de l'utilisation des terres [GIEC, 2014]. Ce dernier est la manifestation la plus évidente des activités humaines, par la déforestation et par la transformation des prairies naturelles en des zones urbaines ou des terres cultivées [DeFries *et al.*, 2004; CEC, 2008]. Par exemple, en date de l'année 2000, une superficie globale de 15 millions de km^2 de savanes, prairies et forêts, a été remplacée par des cultures à des fins agricoles. Cette superficie représente presque 40% de la surface libre de glace de la Terre [Foley *et al.*, 2005]). Les régions les plus touchées étaient le sud de l'Asie, le sud de l'Europe et les États-Unis [Ramankutty *et al.*, 2008; Klein *et al.*, 2011].

Le climat peut être influencé par les changements dans l'utilisation des terres via des interactions biogéochimiques et biophysiques. Les effets biogéochimiques modifient la composition des gaz atmosphériques en augmentant la concentration des gaz à effet de serre, comme le CO_2 et CH_4, ce qui provoque une rétroaction positive de réchauffement [Georgescu et al., 2010; Boysen et al, 2014.; Friedlingstein *et al.*, 2004]. Les effets biophysiques influent sur le budget de l'énergie de surface en modifiant les flux de chaleur sensible, les flux de chaleur latente et le budget de l'eau de surface en altérant la répartition des précipitations dans l'évapotranspiration, le

ruissellement et la teneur en eau du sol [Bonan, 2008; Davin *et al.*, 2010; de Norblet-Ducourdré *et al.*, 2012]. Ces modifications sont une conséquence des changements dans les caractéristiques de surface résultant du remplacement des forêts par des terres cultivées ou des prairies. Par exemple, l'albédo, qui joue un rôle important dans le budget du rayonnement net de la Terre, est plus faible pour les forêts que pour les pâturages ou les terres cultivées. La profondeur des racines, qui détermine la quantité d'eau disponible pour la transpiration, est plus grande pour les arbres comparativement aux cultures, ce qui permet d'extraire davantage d'eau des couches profondes, conduisant donc à des valeurs plus élevées d'évapotranspiration [Bonan, 2008; Pitman *et al.*, 2011; Mahmood *et al.*, 2014].

Pour comprendre l'influence des changements dans l'utilisation des terres, les modèles numériques du climat sont généralement employés [Brovkin *et al.*, 2006] afin de comparer des simulations sans changements dans l'utilisation des terres avec des simulations ayant des changements dans l'utilisation des terres. En utilisant cette méthodologie, des études antérieures ont montré que les changements dans l'utilisation des terres provoquent un refroidissement à l'échelle globale [Brovkin *et al.*, 1999; Feddema *et al.*, 2005; Brovkin *et al.*, 2006], mais qu'il y a beaucoup de disparités au niveau régional. Plus précisément, les modèles ont montré un refroidissement dans les hautes latitudes et les latitudes tempérées latitudes de l'Amérique du Nord, et un réchauffement dans les latitudes tropicales [Laurent et Chase, 2010; Bonan *et al.*, 1997]. Le refroidissement des hautes latitudes peut être directement et/ou indirectement attribué à l'augmentation de l'albédo, à la réduction de longueur de rugosité et à la diminution de l'indice de surface foliaire en raison du changement des forêts par des cultures [Bonan, 2008; Findell *et al.*, 2007; Pitman *et al.*, 2011]. D'autre part, le réchauffement des latitudes tropicales peut être dû à la diminution de l'évapotranspiration et à l'augmentation du flux de chaleur sensible, principalement en raison de la diminution de la profondeur d'enracinement [Pielke, 2001; Fedeman *et al.*, 2005]

Toutefois, il y a encore des incertitudes sur la façon dont les changements dans l'utilisation des terres modifient le climat en raison des questions concernant l'exactitude des les ensembles de données de végétation [Oelson et al., 2004] et sur les caractéristiques des modèles climatiques [Findell et al., 2007]. Par exemple, Hua et Chen (2013) a montré que les changements dans l'utilisation des terres affectent le cycle diurne de température dans les régions des latitudes moyennes de l'Amérique du Nord, de l'Amérique du Sud et de l'Eurasie, et ce, pour la période de 1971 à 2000. Le cycle diurne est effectivement affecté par une augmentation du flux de chaleur latente et une plus grande couverture nuageuse, ce qui entraîne une diminution des températures maximales quotidiennes. Cette étude a également révélé une augmentation de la température minimale quotidienne en Inde, ce qui a entraîné des changements dans l'albédo et l'évapotranspiration. Pitman et al., (2009) ont étudié les impacts des changements dans l'utilisation des terres en utilisant six modèles climatiques globaux (MCG). Leurs résultats suggèrent une diminution statistiquement significative du flux de chaleur latente dans la moitié des MCG, tandis que l'autre moitié montre une augmentation du flux de chaleur latente dans l'hémisphère nord au cours de l'été. D'un autre côté, cinq des six simulations suggèrent une diminution de la température de surface. Ces différences entre les MCG peuvent être attribuées principalement aux différences dans: (a) la configuration des changements dans l'utilisation des terres dans les modèles de végétation de surface, (b) la représentation de la phénologie des cultures, (c) le paramétrage de l'albédo et (d) la représentation de l'évapotranspiration pour différents types d'occupation du sol. Les expériences de modèles climatiques globaux discutés ci-dessus suggèrent que les impacts des changements dans l'utilisation des terres devraient être davantage étudiés de manière régionale [Fedeman et al., 2005; Findell et al., 2007; Pitman et al., 2009; Pielke et al., 2011].

C'est pourquoi des études à l'échelle régionale ont été effectuées afin de mieux comprendre les impacts des changements dans l'utilisation des terres. L'étude de Gao

et al. (2007), étude d'impacts des changements dans l'utilisation des terres sur la région de la Chine, ont constaté que les changements dans l'utilisation des terres permettent (1) le renforcement de la circulation de la mousson, (2) la diminution des précipitations sur les régions méridionales de la Chine, (3) l'augmentation des précipitations sur le nord de la Chine en hiver et (4) un effet de refroidissement de la température moyenne annuelle. Des études sur les régions tropicales ont montré une diminution de l'évapotranspiration, résultant principalement de la diminution de la profondeur des racines en raison des changements dans l'utilisation des terres, conduisant à une augmentation de la température et à une diminution des précipitations [Nogherotto *et al.*, 2013 ; Akkermans *et al.*, 2014.; Lawrence & Vandecar, 2015].

Au cours des dernières années, l'Amérique du Nord a été une région fortement influencée par des changements dans l'utilisation des terres. Son impact a été détecté dans des études antérieures avec des MCG, mais pour une meilleure compréhension de cette influence, il est utile de réaliser des études à l'échelle régionale. Pour cette raison, cette étude se concentre sur les effets biophysiques du changement dans l'utilisation des terres en Amérique du Nord avec une résolution plus élevée, en utilisant la cinquième génération du modèle régional canadien du climat (MRCC5) couplé avec le schéma canadien de paramétrisation de la surface terrestre (CLASS). L'objectif de cette étude est d'évaluer les impacts des changements dans l'utilisation des terres sur le climat en Amérique du Nord en utilisant des expériences soigneusement conçues avec la cinquième génération du modèle régional canadien du climat (MRCC5). Seuls les impacts biophysiques des changements dans l'utilisation des terres seront considérés dans cette étude. Deux simulations utilisant différents ensembles de données de végétation seront produites: (1) avec une végétation potentiel, donc sans l'influence des activités humaines et (2) un ensemble de données qui correspond à l'utilisation actuelle des terres, représenté par l'ensemble de données de végétation potentielle intégré à un ensemble de données de terres cultivées. Les

deux expériences seront comparées entre elles afin d'évaluer les impacts des changements dans l'utilisation des terres sur les caractéristiques de surface et des différents flux.

Organisation du mémoire

Pour faire suite à cette introduction, un article rédigé en anglais correspond au chapitre II de ce mémoire. Cet article comprend l'Introduction (section 2.1) pour discuter du cadre théorique et l'objectif de l'étude. Puis, il y les descriptions du modèle et de la Méthodologie (section 2.2), suivi de la présentation des Résultats (section 2.3) qui se concentrent sur la comparaison entre simulations pour les saisons d'hiver et d'été, et sur l'évaluation de variables de surface et de cycles annuels. Finalement, la section 2.4 fournit le résumé et les conclusions de cet article. Les conclusions de ce mémoire seront présentées au chapitre III et le chapitre IV liste les références.

CHAPITRE II

LES IMPACTS BIOPHYSIQUES DES·CHANGEMENTS DE L'UTILISATION
DES TERRES EN AMÉRIQUE DU NORD AVEC LE MODÈLE RÉGIONAL DU
CLIMAT CANADIEN

Ce chapitre, présenté sous forme d'un article rédigé en anglais, est principalement
concentré sur les impacts biophysiques des changements de l'utilisation des terres sur
l'Amérique du Nord avec la cinquième génération du Modèle Régional Canadien du
Climat (MRCC5). Ce chapitre contient les descriptions du MRCC5, des expériences,
des résultats et des conclusions.

BIOPHYSICAL IMPACTS OF LAND USE CHANGE OVER NORTH AMERICA AS SIMULATED BY THE CANADIAN REGIONAL CLIMATE MODEL

by

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Abstract

This study investigates the biophysical impacts of human-induced land use change (LUC) on the regional climate of North America, using the fifth generation Canadian Regional Climate Model (CRCM5). To this end, two simulations are performed with CRCM5 using different land cover datasets, one corresponding to the potential vegetation and the other corresponding to current land use, spanning the 1988–2012 period, driven by European Centre for Medium-Range Weather Re-Analysis (ERA)-Interim at the lateral boundaries. Comparison of the two suggests higher albedo values, and therefore cooler temperatures, over the LUC regions, in the simulation with LUC, in winter. This is due to the absence of crops in winter, and also possibly due to a snow-mediated positive feedback. Some cooling is observed in summer for the simulation with LUC, mostly due to the higher latent heat fluxes and lower sensible heat fluxes over eastern US. Precipitation changes for these regions are not statistically significant. Analysis of the annual cycles for two LUC regions suggests that the impact of LUC on two meter temperature, evapotranspiration, soil moisture and precipitation are present year round. However, the impact on runoff is mostly restricted to the snowmelt season. This study thus highlights regions and variables most affected by LUC over North America.

Keywords: biophysical impacts; land use change; regional climate modeling; North America

2.1   Introduction

The climate and the general environment of our planet have been strongly modified by human activities [Mahmood *et al.*, 2010] through time that are reflected in changes in emissions of trace gases into the atmosphere and land use change (LUC) [IPCC, 2014]. However, the most obvious manifestation of human activities is seen in the latter, in the form of deforestation or transformation of natural grasslands into urban or cropland areas [DeFries *et al.*, 2004; CEC, 2008]. As of year 2000, savannas, grasslands and forests, with a global area of 15 million km^2 (which is almost 40% of Earth's ice free land surface [Foley *et al.*, 2005]), have been replaced for agricultural purposes, with LUC being largest over south and southeast Asia, Europe and the United States (US) [Ramankutty *et al.*, 2008; Klein Goldewijk *et al.*, 2011].

Climate can be influenced by LUC through biogeochemical and biophysical interactions. The biogeochemical effects alter the atmospheric gas composition by modifying greenhouse gases, such as CO_2 and CH_4; this increase in the concentration of greenhouse gases can further augment climate warming through a positive feedback [Georgescu *et al.*, 2010; Boysen *et al.*, 2014; Friedlingstein *et al.*, 2004]. The biophysical effects influence the surface energy budget by altering the sensible and latent heat fluxes and the surface water budget by alterating the partitioning of precipitation into evapotranspiration, runoff and soil water content [Bonan, 2005; Davin *et al.*, 2010; Norbley-Ducourdré *et al.*, 2012]. These alterations are a consequence of the changes in surface characteristics resulting from replacing forests by croplands or grasslands. For example, forests have lower albedo than pastures or croplands. Therefore, clearing forests or transforming grasslands to croplands results in higher albedo values. Another important variable is root depth, which determines transpiration. Trees with deeper roots compared to crops extract water from deeper layers, leading to higher evapotranspiration values [Bonan, 2008; Pitman *et al.*, 2011; Mahmood *et al.*, 2014].

To understand the influence of LUC, numerical climate models are generally employed [Brovkin *et al.*, 2006]. Usually, two simulations, with and without LUC, are performed with global or regional climate model to assess the impact of LUC. Using this methodology, past studies have shown that LUC causes a cooling at the global scale [Brovkin *et al.*, 1999; Feddema *et al.*, 2005; Brovkin *et al.*, 2006], though there are important differences regionally. LUC is shown to cool temperatures in the high and temperate latitudes of North America, while warming is noted for the tropical latitudes [Lawrence and Chase, 2009; Bonan *et al.*, 1997]. This can be directly and/or indirectly attributed to increases in albedo, reduction in roughness length and leaf area index due to the change of forest to crops in high and temperate latitudes [Bonan, 2005; Findell *et al.*, 2007; Pitman *et al.*, 2011]. On the other hand, the LUC associated warming presented in the tropical latitudes is due to the reduction of evapotranspiration and an increase in sensible heat flux, primarily due to the decrease in rooting depth [Pielke, 2001; Fedeman *et al.*, 2005].

Nevertheless, there is still uncertainty about how LUC alters the climate due to questions about the accuracy of the vegetation datasets [Oelson *et al.*, 2004] and the characteristics of the climate models [Findell *et al.*, 2007]. For example, Hua and Chen (2013), in their global scale study, for the period of 1971 to 2000, found that LUC affects the diurnal temperature range in the mid-latitude regions of North America, South America and Eurasia and increases the latent heat flux, enhancing the cloud cover, thus resulting in decreased daily maximum temperatures. This study also found a decrease in the diurnal temperature range over India that was due to an increase in the daily minimum temperature, which resulted from changes in albedo and evapotranspiration. Pitman *et al.* (2009) studied the impact of LUC using six global climate models (GCMs), and their results suggest statistically significant decreases in the latent heat flux in three GCMs and increases in the other three GCMs, for the northern hemisphere during summer. However, for the near-surface temperature five GCMs suggest cooling and the sixth one suggests warming. These

differences between the GCMs can be attributed primarily to the differences in: (a) the implementation of LUC in the vegetation/land surface models, (b) representation of crop phenology, (c) parametrization of albedo and (d) representation of evapotranspiration for different land cover types, among others. Despite these differences, the above discussed GCM experiments suggest that the impacts of LUC are more regional in nature [Fedeman *et al.*, 2005; Findell *et al.*, 2007; Pitman *et al.*, 2009; Pielke *et al.*, 2011].

Taking this into consideration, studies at regional scale have been performed to further understand the impact of LUC. For example, Gao *et al.*, (2007) in their study of the impacts of LUC over China found that LUC reinforces the monsoon circulation, reduces precipitation over the southern regions of China and increases precipitation over the north in winter (opposite situation happens during summer), and causes a cooling effect in the annual mean temperature. Regional studies over tropical regions, confirming global studies discussed above, have shown that a decrease in evapotranspiration, mainly resulting from the reduction in root depth due to LUC, leads to an increase in temperature and a reduction in precipitation [Nogherotto *et al.*, 2013; Akkermans *et al.*, 2014; Lawrence & Vandecar 2015].

In the past years, North America has been a region greatly influenced by LUC. Its impact was detected in past studies with GCMs, but for better understanding of this influence, it is useful to perform regional scale studies. For this reason, this study is focused on the biophysical effects of LUC over North America in a higher resolution, using the fifth generation Canadian Regional Climate model (CRCM5) coupled with the Canadian Land Surface Scheme (CLASS). Two simulations using different vegetation datasets are used: (1) a potential vegetation dataset without the influence of human activities and (2) a dataset that corresponds to current land use, represented by the potential vegetation dataset modified for land use using a cropland dataset. The aim of this study is to understand how climate has been altered by the change in

potential vegetation due to land use changes and how this change affects surface characteristics and fluxes for various seasons.

The paper is organized as follows. A brief description of the model and the methodology is presented in section 2.2. The impacts of land use change are presented in section 2.3, followed by summary and conclusions in section 2.4.

2.2 Model and Methods

2.2.1 The Canadian Regional Climate Model

The model used in this study is CRCM5 [Martynov *et al.*, 2012], which is based on a limited-area version of the Global Environment Multiscale (GEM) model used for Numerical Weather Prediction (NWP) at Environment Canada [Côté *et al.*, 1998]. GEM employs semi-Lagrangian transport and (quasi) fully implicit stepping scheme. In its fully elastic non-hydrostatic formulation [Yeh *et al.*, 2002], GEM uses a vertical coordinate based on hydrostatic pressure [Laprise, 1992]. The following GEM parameterisations are used in CRCM5: deep convection following Kain and Fritsch (1990), shallow convection based on a transient version of Kuo (1965) scheme [Bélair *et al.*, 2005], large-scale condensation [Sundqvist *et al.*, 1989], correlated-K solar and terrestrial radiations [Li and Barker, 2005], subgrid-scale orographic gravity-wave drag [McFarlane, 1987], low-level orographic blocking [Zadra *et al.*, 2003], and turbulent kinetic energy closure in the planetary boundary layer and vertical diffusion [Benoit *et al.*, 1989; Delage and Girard, 1992; Delage, 1997].

The land surface scheme in CRCM5 is the Canadian Land Surface Scheme [CLASS, Verseghy 1991, 2011; Verseghy *et al.*, 1993]. CLASS is set up with 26 soil layers reaching a depth of 60 m, instead of the default three layers with a total depth of 4.1 m, in this study. It includes prognostic equations for energy and water conservation, and a thermal and hydrologically distinct snowpack where applicable (treated as a variable-depth layer). The hydrological budget is calculated only for the layers above

the bedrock, but the energy balance and the thermal budget are calculated for the whole soil depth. In an attempt to crudely mimic subgrid-scale variability, CLASS adopts a pseudo-mosaic approach and divides each grid cell into a maximum of four sub-areas: bare soil, vegetation, snow over bare soil and snow with vegetation. For each sub-area the water and energy balance are calculated separately and then averaged over the grid cell. Also, CLASS recognizes 4 main vegetation categories: needleleaf trees, broadleaf trees, crops and grasses. For each type of vegetation, the structural attributes such as leaf area index, roughness length, canopy mass and rooting depth have to be specified if they are present in a grid cell.

2.2.2   Methodology

The aim of this study as discussed above is to assess the impact of LUC on the North American climate. To this end, as mentioned earlier, two CRCM5 simulations, with different land cover datasets, i.e. one with potential vegetation, or in other words vegetation that would exist if the region was void of human activity, and the other representing exclusively the present-day land use of cropland, are performed. These simulations will be referred to as CRCM5_PV and CRCM5_LUC, hereafter.

The potential vegetation dataset used in CRCM5_PV comes from Ramankutty and Foley (1999), which includes 15 vegetation types, available at 5 min resolution. This dataset is mainly derived from the DISCover dataset [Loveland and Belward, 1997] for the April 1992 to March 1993 period, where the potential vegetation for areas subject to land use were modified using the dataset of Haxeltine and Prentice (1996). More details about this dataset can be found in Ramankutty and Foley (1999).

A new vegetation dataset obtained by merging the potential vegetation dataset from CRCM5_PV and the cropland dataset of Ramankutty *et al.* (2008) is used in CRCM5_LUC. Ramankutty *et al.* (2008) compiled this cropland dataset such that it is consistent with the Food and Agriculture Organization's (FAO) definition of 'Arable lands and permanent crops' and signifies one of the most important impacts that

humans have had on LUC. This dataset is created by combining global agricultural inventories from 1998 to 2002 (the proxies for that period were used when data were unavailable) along with data from satellites from the Boston University's Moderate resolution Imaging Spectrometer (BU-MODIS) [Friedl *et al.*, 2002] and the Satellite Pour l'Observation de la Terre (SPOT) VEGETATION [Bartholome and Belward, 2005]. The potential vegetation fractions were reduced for cells with LUC in CRCM5_LUC, such that the total fractional area is 1.

The CRCM5 simulations are performed over a grid covering North America and adjoining oceans (Figure 2.1), at 0.44° horizontal resolution (~50 km), for the 1979-2012 period. The soil moisture and temperature fields are initialized with values obtained by spinning CLASS offline for 100 years, driven by European Centre for Medium-Range Weather Forecasts Reanalysis (ERA)-40 reanalysis for the 1958-1978 period repeatedly, using respective vegetations in the two spin-up simulations. The CRCM5 simulation for the 1979-2012 period were driven at the lateral boundaries by ERA-Interim reanalysis data [Dee *et al.*, 2011] from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the first 9 years are considered as spin-up and therefore not included in the analysis presented in the paper. The ERA-Interim data is available at 0.75° horizontal resolution (~ 80 km). The fractioned areas of the 4 main categories of vegetation considered for CRCM5_PV and CRCM5_LUC simulations are shown in Figure 2.2.

In CRCM5_LUC simulation, large parts of the grasslands over the central regions of the US and the Canadian prairies, are replaced with cropland. Small fractions of broadleaf and needleleaf are also replaced with crops, particularly in the north-east US and central Canada. The seasonal variations in the morphological characteristics of the 4 main vegetation categories are taken into account in CLASS [Verseghy, 1991 and Verseghy *et al.,* 1993]. During maturity and/or fully leafed periods, the growth index has a value of 1, while it is 0 during leafless periods. The transition period

between these two states is assumed to be linear, lasting up to 2 months for needleleaf trees and up to 1 month for broadleaf trees. For the growth index of crops, Earth is divided in 10° latitudinal bands (in both hemispheres). The start of growing season and the end of harvest are set to occur on certain days of the year based on average dates from the Food and Agriculture Organization of the United Nations (UN FAO) for regions above 30°N. It is assumed that it takes 2 months for crops to reach maturity and 1 month between the beginning of senescence and the end of harvest. For grass, the growth index is set at 1 all year round because the annual variation in height and leaf area index are negligible. The roughness length of trees does not undergo seasonal variation, therefore is always equal to the maximum value. The height of crops and grasses varies (lower than the maximum height) because of partial burying by snow and, for crops, an immature growth stage. The rooting depth of trees and grasses remain at their maximum values as they are not affected by snow cover. However, for crops, it is corrected for its growth stage. The leaf area index presents seasonal variations and ranges between its minimum and maximum values. For trees, this variable is unaffected by the presence of snow. As for crops and grasses, the presence of snow must be taken into account for its calculation. On the other hand, for trees, both visible and near-infrared albedo are set to their average observed values but under leafless conditions, different values are set for the case of snow-cover and that of snow-free ground under the canopy. When half of the leaves have fallen, albedo varies linearly with leaf area index. For crops and grass, the leaf area index does not go below 1; therefore, the albedo values remain and do not vary from fully leafed values except when the ground is snow-covered. CLASS simulates reasonably well the seasonal variations in the canopy parameters, when proper fractional vegetation cover is specified. Validation of the previous version of CLASS has been performed as part of Project for Inter-comparison of Land Surface Parameterization (PILPS) [Henderson-Sellers *et al.*, 1995; Henderson-Sellers *et al.*, 1996; Pitman & Henderson-Sellers, 1998]. Langlois *et al.* (2014) and Haghnegahdar

et al. (2014), have evaluated the performance of the recent version 3.5 of CLASS, but when coupled with RCMs, focusing on snow simulations and hydrological modelling.

The biophysical effects of LUC over North America on selected surface variables and fluxes are assessed by comparing CRCM5_LUC and CRCM5_PV simulations. The statistical significance of these differences is assessed through a t-test at 95% confidence level.

2.3   Results

2.3.1   Spatial Seasonal Analysis

The differences between CRCM5_LUC and CRCM5_PV for the winter and summer months are presented here. References are made to other seasons where required.

Figure 2.3 shows the differences between CRCM5_LUC and CRCM5_PV for selected surface fluxes and variables for the winter season. Regions with statistically significant differences in leaf area index (LAI) show a dipole pattern, with smaller LAI values in the north and higher values in the south in CRCM5_LUC compared to CRCM5_PV (Figure 2.3a). This is because, for the northerly regions, the growing season for crops is mostly limited to the spring—early fall periods, leading to zero LAI in winter in CRCM5_LUC. However, for the southern regions (below 30°N), growing season for crops is year round as for broadleaf trees and therefore the LAI values are higher in CRCM5_LUC compared to CRCM5_PV (Figure 2.3a). Note that for this southern region, fractional areas of both grass and broadleaf were replaced with crops. The above changes to LAI leads to statistically significant differences in albedo between CRCM5_LUC and CRCM5_PV over these LUC regions, particularly for the northern regions (Figure 2.3b), where albedo values are higher in CRCM5_LUC compared to CRCM5_PV. The regions south of 30°N show slightly higher values of albedo in CRCM5_LUC, despite the higher values of LAI, which is due to relatively drier soil layer at the surface in this simulation. The higher values of

albedo in CRCM5_LUC are reflected in the negative differences in sensible heat flux (SHF, Figure 2.3c) and two meter temperatures (T2M). The differences in T2M is more than 1.4°C over central Canada and central east US (Figure 2.3d). The signature of high albedo in CRCM5_LUC can also be seen in the lower values of the daily minimum (TMin) and maximum (TMax) temperatures; the maximum differences between CRCM5_LUC and CRCM5_PV for these temperatures are 1.4°C and 1.7°C, respectively (Figure 2.3^e and f). The cooler temperatures in CRCM5_LUC lead to boundary layer heights that are 80 to 200 m lower than that in CRCM5_PV in LUC affected regions. Snow water equivalent presents higher values over central Canada and central-east US (Figure 2.3h), in CRCM5_LUC, which is due to cooler temperatures in this simulation. The higher snow water equivalent values can further increase the albedo values, leading to further cooling and snow water equivalent augmentation through snow-albedo feedback. Furthermore, high values of runoff are noted during spring in CRCM5_LUC, which is consistent with the higher snow water equivalent values in this simulation (Figure 2.3 h and i), as spring runoff is primarily related to snow melt.

The impacts of LUC during the summer season are presented in Figure 2.4. The differences in LAI between CRCM5_LUC and CRCM5_PV are statistically significant over a larger region, covering regions with important LUC and adjoining areas (Figure 2.4a). For southerly regions (south of 50°N), the differences are positive, suggesting higher LAI, while for northerly regions (north of 50°N) it is negative, suggesting lower LAI in CRCM5_LUC compared to CRCM5_PV. These negative values for the northern regions are due to shorter growing season of crops, compared to that of grass (which is year round in the model), leading to lower average LAI values. For the northerly regions (north of 50°N) the onset (harvest) happens later (earlier), compared to southern regions. The higher values of LAI for the regions south of 50°N is due to the higher LAI values of crops compared to grass for this region. The regions with significant differences in LAI also show statistically

significant differences in albedo (Figure 2.4b), with albedo being higher in CRCM5_LUC.

The differences in albedo for summer are much smaller than that for winter. The higher values of albedo in CRCM5_LUC for the northern regions is primarily due to the lower LAI values, while for the southern regions, the noted higher values of albedo, despite higher LAI values is partly due to the drier surface soil layers due to increased evaporation. The differences in albedo are reflected in the reduced SHF values over the central and eastern parts of the US in CRCM5_LUC (Figure 2.4c). The latent heat flux (LHF), on the other hand, appears higher in CRCM5_LUC due to higher LAI for these regions. The lower SHF, and the increased LHF and associated evaporative cooling lead to cooler temperatures in CRCM5_LUC (Figure 2.4c). This is also reflected in the TMin, TMax and in the soil temperatures (Figure 2.4f–h).

The comparison of the 10 m wind field between CRCM5_LUC and CRCM5_PV shows statistically significant high wind magnitude values over a small region of northeast US during winter and summer seasons (Appendice B). These high values could be a response to the replacement of broadleaf trees with crops. In central US, statistically significant changes in wind magnitude are observed, where lower values are displayed in both seasons. However, the differences are smaller than 0.5 m/s and 0.25 m/s for summer and winter, respectively (Annexe A). These two small zones, northeast and central US, present changes in the wind field but do not show that LUC impacts circulation and are not indicative of a LUC influenced teleconnection over North America.

2.3.2 Analysis of Average Annual Cycles

Results presented above show that the statistically significant differences are mostly collocated with regions of important LUC. Therefore, two regions, zone 1 and zone 2, are defined to look carefully at the differences in the annual cycles in CRCM5_LUC and CRCM5_PV of selected surface variables. Zone 1 covers 46°-60°N and 94°-

114.5°W, and includes central Canada and a small region of northern central US. Zone 2 covers 31°-46°N and 80-103°W, which includes most of the LUC regions in the central to eastern US (Figure 2.1).

In order to evaluate the LUC effects over these zones, grid points with crops in the CRCM5_LUC simulation in zones 1 and 2 are selected for analyzing the mean annual cycles in both CRCM5_LUC and CRCM5_PV simulations (Figure 2.5, 2.6 and 2.7). The annual cycle of albedo shows high values from January to April and from October to December and low values during the summer months, as expected, due to the presence of snow during the late winter to early spring seasons. Both zones present the same tendency, but zone 2 has lower values in winter compared to zone 1, given its southerly location (Figure 2.5a). The annual cycle of the differences between the two simulations, suggest larger differences during the fall to spring periods (Figure 2.5b). Differences in albedo between the two simulations are larger for zone 1 compared to zone 2, mainly due to the larger differences in snow water equivalent over zone 1 (Figure 2.5b and f). This relationship reinforces the snow-albedo feedback, as suggested before, during winter months (Figure 2.5a and e). The higher snow water equivalent values in CRCM5_LUC leads to higher spring peak flows for both zones as shown in Figure 2.6a. The differences are again larger for zone 1 compared to zone 2 due to its northern location (Figure 2.5b). Generally higher runoff values are noted for all months, except for summer and begining and end of fall and spring, respectively. The maximum differences in runoff occur at different times for the two zones (Figure 2.6b). This is due to the fact that snowmelt starts one month earlier in zone 2 because of its geographic location. As for the period of May to October, as discussed earlier, the differences between the two simulations are near zero since runoff is mostly coming from baseflow and surface runoff during precipitation events. Note that no significant differences are noted for precipitation for the two zones.

Figure 2.5c shows the annual cycle of T2M. The comparison between CRCM5_LUC and CRCM5_PV shows that the cooling effect of LUC occurs throughout the year; it is however higher from January to April, with differences higher than 0.9°C (Figure 2.5d). The cooling over this period is related to high albedo and snow water equivalent values in CRCM5_LUC as already disccussed (Figure 2.5). On the other hand, the CRCM5_LUC cooling trend observed from May to September is related to higher evapotranspiration values, which is particularly noticeable over zone 2 (Figure 2.5a, b, 2.6c and d). Maximum evapotranspiration is observed in June and July for zone 1 and 2, respectively (Figure 2.6c). As for the difference between the simulations, CRCM5_LUC for zone 2 shows higher evapotranspiration values over the period of June to November, mostly during the presence of crops over that zone. As for zone 1, the higher evapotranspiration differences are noted from June to August and are smaller than for zone 2, mainly due to shorter growing season in this zone compared to zone 2 (Figure 2.6d).

The annual cycle of integrated soil moisture shows high values during snowmelt, for both zones (Figure 2.6 e). During the warm months, there is a decreasing tendency in soil moisture as a result of high evapotranspiration (Figure 2.6e). The integrated soil moisture is higher in the CRCM5_LUC experiment for both zones. The integrated soil moisture is generally higher for zone 1, compared to zone 2, despite the higher values of precipitation for zone 2 compared to zone 1 (Figure 2.7a). The lower values for zone 2 are related partly to the higher rate of evapotranspiration and partly due to relatively shallow depth to bed rock (figure not shown). The differences in soil moisture between CRCM5_LUC and CRCM5_PV are smaller for zone 1 (Figure 2.6f), compared to zone 2. The differences in precipitation between the two simulations are small (Figure 7b). The precipitation is slightly higher in CRCM5_LUC during the summer months for zone 1 and zone 2, but the differnces are not statistically significant.

2.4   Discussion and conclusions

The biophysical effects of LUC can result in cooling or warming depending on the duration of the growing season, changes in albedo and partitioning of available energy between sensible and latent heat fluxes. The two CRCM5 simulations considered in this study, with and without LUC, suggest significant impacts of LUC on the regional climate of North America. The results show a cooling effect over the LUC regions during winter and summer. The mechanisms leading to this cooling are different for the two periods. The cooling effect of LUC in winter is more than 1.4 °C.

This is mainly attributed to the high albedo values in LUC regions, which is further enhanced via snow-albedo feedback, in agreement with Bonan G. (2008), Feddeman *et al.* (2005) and Brovkin *et al.* (1999). As for the summer season, the regions with statistically significant cooling are smaller, with differences in two meter temperature values less than 1.2 °C. The cooling here is primarily due to high (low) latent (sensible) heat flux values. The above impacts of LUC are congruent with the studies of Bonan (1997) and Oleson *et al.* (2004) where they report cooler temperatures over the LUC regions of North America in summer season because of high latent heat flux values.

Two zones were analyzed to further understand the influence of LUC, one covering central Canada and the other central east US, using only grid points with crops in the simulation with LUC. Analysis of the seasonal cycles for both simulations suggests that the cooling effect of LUC is present year round. The impacts of LUC on evapotranspiration and soil moisture are also year round. However, the impact on runoff is mostly restricted to snowmelt season. It should be noted that the precipitation differences are not statistically significant. This could be due to the weak soil moisture-precipitation coupling over the Great Plains in CRCM5 as discussed in Diro *et al.* (2014). Furthermore, the absence of irrigation in

CRCM5_LUC, could also contribute to the non-significant differences in precipitation between the two simulations.

In this study, only croplands were used to represent human activity over North America and the biophysical effects of this LUC were evaluated. The influence of irrigation over croplands is not included, but it would be important to implement it in future regional climate simulations. Studies, however, have been done using GCMs that include irrigation. For example, Haddeland *et al.* (2006) in their study used an irrigation scheme over Colorado and Mekong River basins and found that latent heat flux increases along with a decreases of temperature, over these areas. This was identified over large fraction of grid cells where the irrigation was implemented. Lo and Famiglietti (2013), in their study using a regional climate model with irrigation over the central valley of California, showed that irrigation leads to an increase in evapotranspiration leading to net land surface cooling. Another important influence was an increase in precipitation, mainly in summer, enhancing the monsoon rainfall over the southwest US.

It must also be noted that sub-grid lakes and wetlands were not considered in this study. These should also be included in futures studies. Furthermore, future studies should also take into account pastures, urban areas and disturbances such as fire. It is also important to consider LUC in transient climate change simulations with regional climate models. Currently, many regional climate models do not include this. Studies with global climate models have shown that urbanization leads to warming at regional and local scales, pastures lead to cooling over temperate zones and fires lead to decreases in precipitation due to reduced evapotranspiration [Boysen *et al.*, 2014; He *et al.*, 2007; Cochrane & Laurance, 2008]. CRCM5 transient climate change simulations, including land use change will be performed in the near future to investigate the biophysical effects of LUC on projected changes to the surface climate and hydrology over North America.

Acknowledgments

CHAPITRE III

CONCLUSION

Des études récentes sur les impacts des changements de l'utilisation des terres qui utilisaient des modèles climatiques globaux ont démontré que ces impacts sont propres à la localisation de la région étudiée. C'est pourquoi plusieurs études avec des modèles climatiques régionaux ont été menées sur différentes régions afin de comprendre les impacts locaux des changements de l'utilisation des terres. Dans cette étude, nous avons évalué les impacts des changements de l'utilisation des terres en Amérique du Nord en utilisant la cinquième génération du Modèle Régional Canadien du Climat (MRCC5).

Pour ce faire, deux simulations du MRCC5 ont été effectuées sur une grille couvrant essentiellement l'Amérique du Nord à 0,44° de résolution horizontale (~ 50 km), pour la période de 1979 à 2012. Les deux simulations se différencient de par les ensembles de données fournissant la couverture terrestre. La première simulation, nommée CRCM5_PV, est réalisée avec la végétation potentielle, ou en d'autres termes, la végétation qui existerait si la région était sans activités humaines. L'ensemble de données de végétation potentielle utilisée dans cette étude suit Ramankutty et Foley (1999), qui comprend 15 types de végétation, disponibles à une résolution temporelle de 5 min. La deuxième simulation, nommée CRCM5_LUC, représente l'utilisation actuelle des terres, créé par la fusion des données de végétation potentielle et des

données de terres cultivées qui représente les terres agricoles de l'année 2000 suivant l'étude de Ramankutty *et al.* (2008). Les deux simulations sont pilotées par ERA-Interim aux frontières latérales pour la période de 1979 à 2012 et les neuf premières années correspondent au spin-up de la simulation et ne sont donc pas considérées dans l'analyse de cette étude.

Les deux simulations du MRCC5 montrent que le changement de la végétation potentielle en terres cultivées influence le climat régional de l'Amérique du Nord, avec des températures plus basses sur les régions des changements de l'utilisation des terres pendant l'hiver et l'été. Les mécanismes conduisant à ce refroidissement sont différents pour les deux saisons. L'effet de refroidissement dû aux changements de l'utilisation des terres en hiver est de 1,4 °C. Ceci est principalement attribuable à la rétroaction positive entre les valeurs plus élevées de l'albédo et la neige dans les régions des changements de l'utilisation des terres. Pour la saison estivale, le refroidissement dû aux changements de l'utilisation des terres est moins important, avec des différences de 1,2 °C dans la température à 2 mètres. Ceci est principalement dû à des valeurs élevées (faibles) des flux de chaleur latente (sensible). Les impacts des changements de l'utilisation des terres sont en accord avec les études de Bonan (1999) et Oleson *et al.* (2004), où ils rapportent des températures plus basses sur les régions des changements de l'utilisation des terres en Amérique du Nord pour la saison estivale en raison des valeurs plus élevées des flux de chaleur latente.

Deux sous-régions ont été analysées afin de mieux comprendre l'influence locale des changements de l'utilisation des terres. L'une couvre le centre du Canada et l'autre le centre-est des États-Unis (Figure 2.1). L'analyse des cycles saisonniers pour les deux simulations suggère que l'effet de refroidissement des changements de l'utilisation des terres est présent toute l'année. Les impacts des changements de l'utilisation des terres sur l'évapotranspiration, l'humidité du sol et les précipitations sont également

présents toute l'année. Cependant, l'impact sur le ruissellement est principalement limité à la saison de la fonte des neiges.

Dans cette étude, seules les terres cultivées ont été utilisées pour représenter l'activité humaine en l'Amérique du Nord et seuls les effets biophysiques des changements de l'utilisation des terres ont été évalués. Des études futures devraient également prendre en considération les pâturages, les zones urbaines et les perturbations comme les incendies. Il est également important de considérer les impacts des changements de l'utilisation des terres dans un contexte de changements climatiques avec des modèles climatiques régionaux. Des études avec des modèles climatiques globaux ont montré que l'urbanisation peut conduire à un réchauffement local, les pâturages peuvent conduire à un refroidissement sur les zones tempérées et les feux de forêts peuvent entrainer une baisse des précipitations en raison d'une évapotranspiration réduite [Boysen *et al.*, 2014.; He *et al.*, 2007; Yao *et al.*, 2015 et Cochrane et Laurance, 2008]. Les études futures devraient donc analyser les changements projetés des effets biophysiques des changements de l'utilisation des terres sur l'hydrologie de surface et le climat en Amérique du Nord.

APPENDICE A

FIGURES

Figure 2.1   Sub-section 2.2.2 : Methodology

Section 2.3 : Results

Section 2.4 : Summary and conclusions

Figure 2.2   Sub-section 2.2.2 : Methodology

Figure 2.3   Section 2.3 : Results

Figure 2.4   Section 2.3 : Results

Figure 2.5   Section 2.3 : Results

Figure 2.6   Section 2.3 : Results

Figure 2.7   Section 2.3 : Results
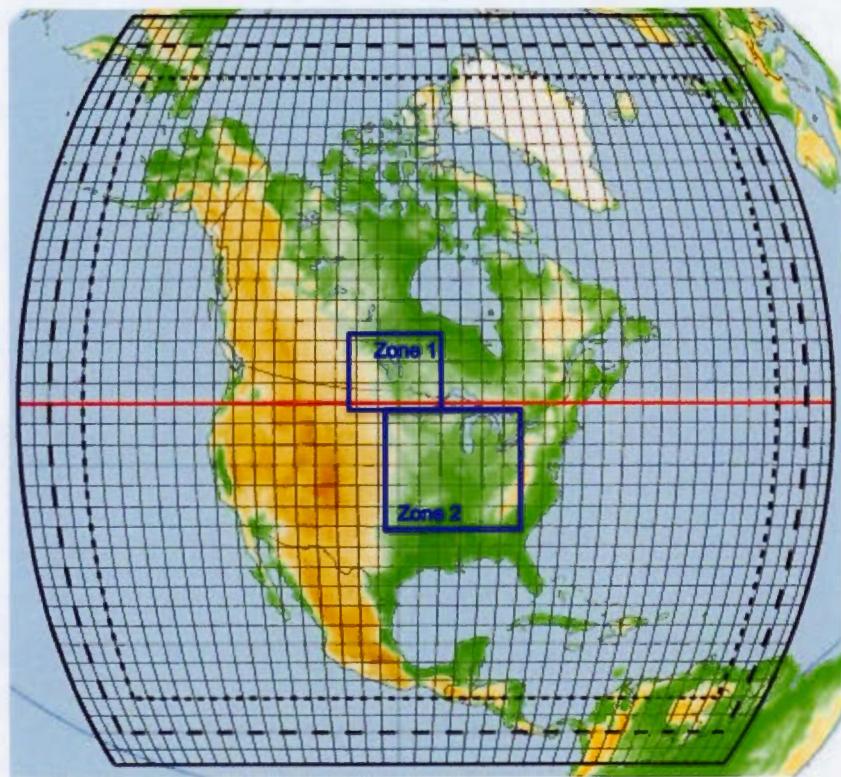
Figure 2.1 Simulation domain: 220 x 200 points grid at 0.44° horizontal resolution grid (only every 5th grid point is displayed). The dashed and dotted lines represent the 'halo' and sponge zones, respectively. The remaining is the free domain of 160 x 180 grid points. The two blue boxes represent regions considered for analyzing the seasonal cycle (zone 1 covers 46°-60°N and 93°-121°W and zone 2 covers 31°-46°N and 80-108°W).
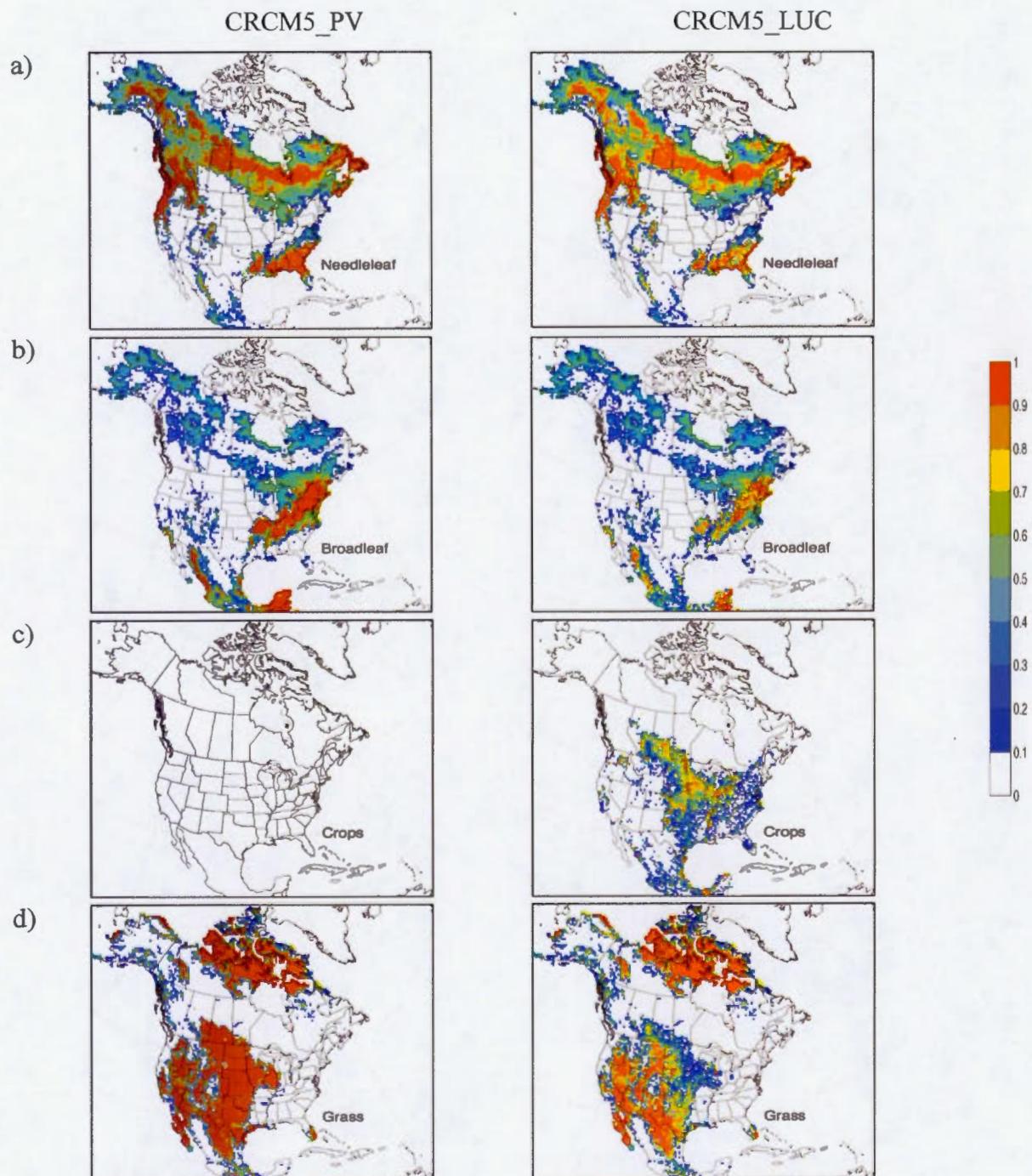
Figure 2.2 a) Needleleaf, b) broadleaf, c) crop and d) grass fractional areas for CRCM_PV (left panels) and CRCM_LUC (right panels).
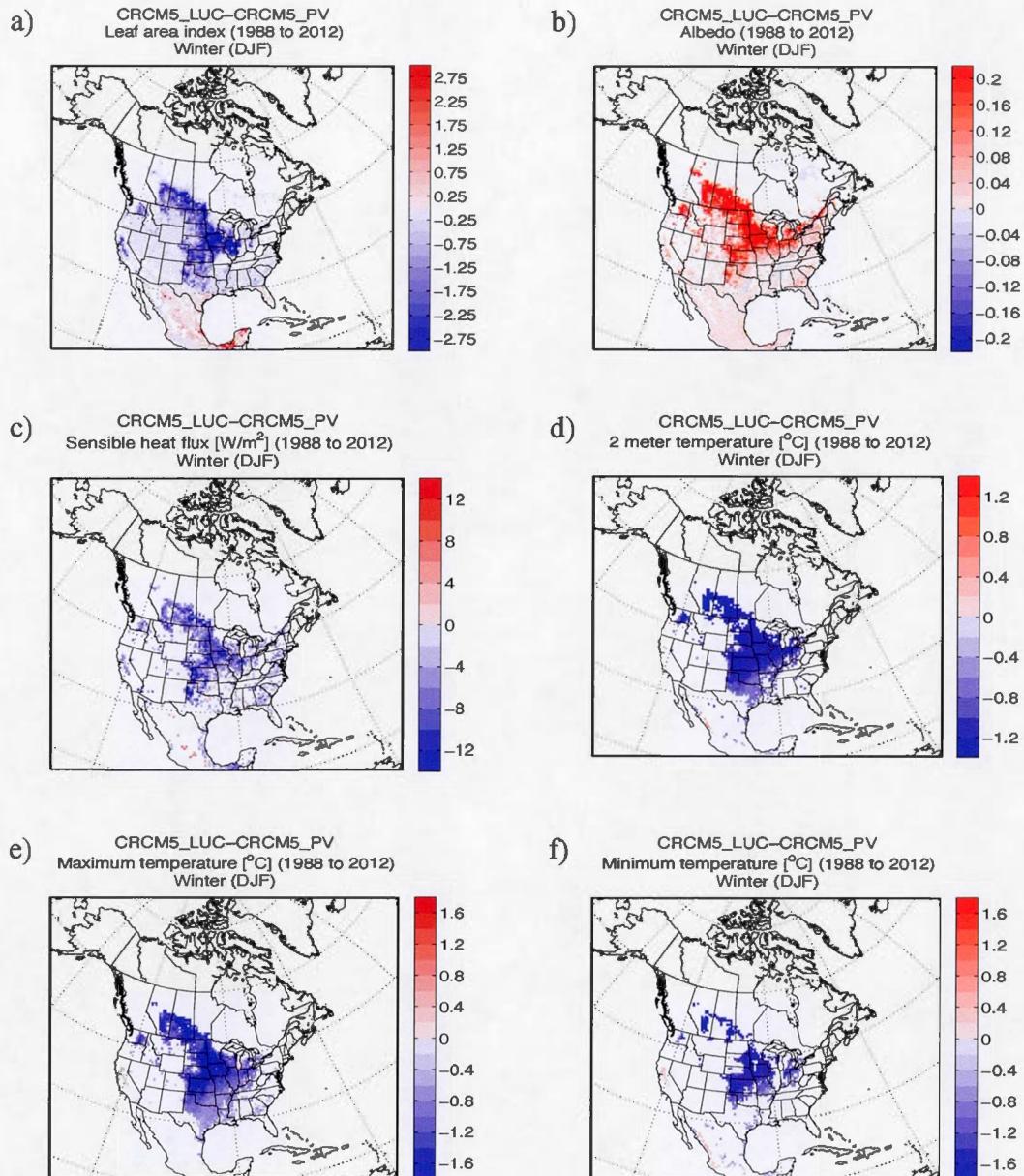
Figure 2.3 Differences between CRCM_LUC and CRCM_PV, for winter, for (a) leaf area index, (b) albedo, (c) sensible heat flux, (d) maximum temperature, (e) minimum temperature, (f) two meter temperature, (g) height of the bounday layer, (h) snow depth and (i) runoff. Values are shown only for grid points where the differences are statisitcally significant at 95% confidence level.

g)

CRCM5_LUC–CRCM5_PV
Height boundary layer [m] (1988 to 2012)
Winter (DJF)

h)

CRCM5_LUC–CRCM5_PV
Snow water equivalent [cm] (1988 to 2012)
Winter (DJF)

i)

CRCM5_LUC–CRCM5_PV
Runoff [mm/day] (1988 to 2012)
Spring (MAM)
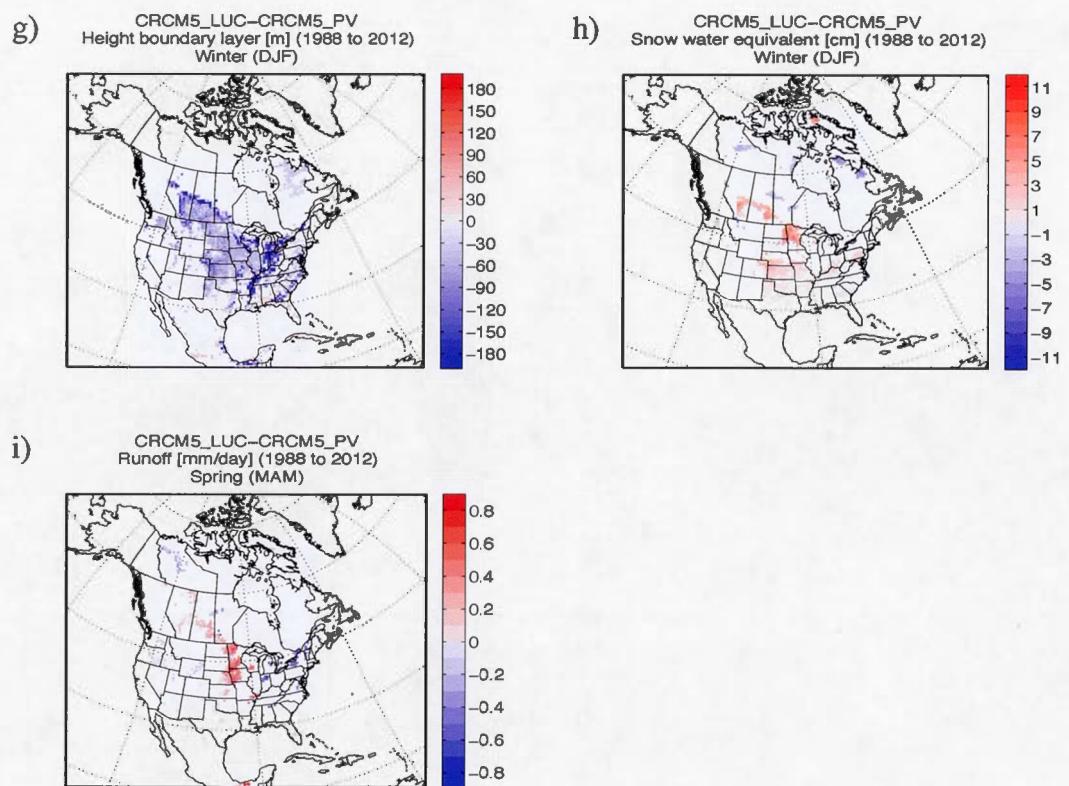
**Figure 2.3** (continued)
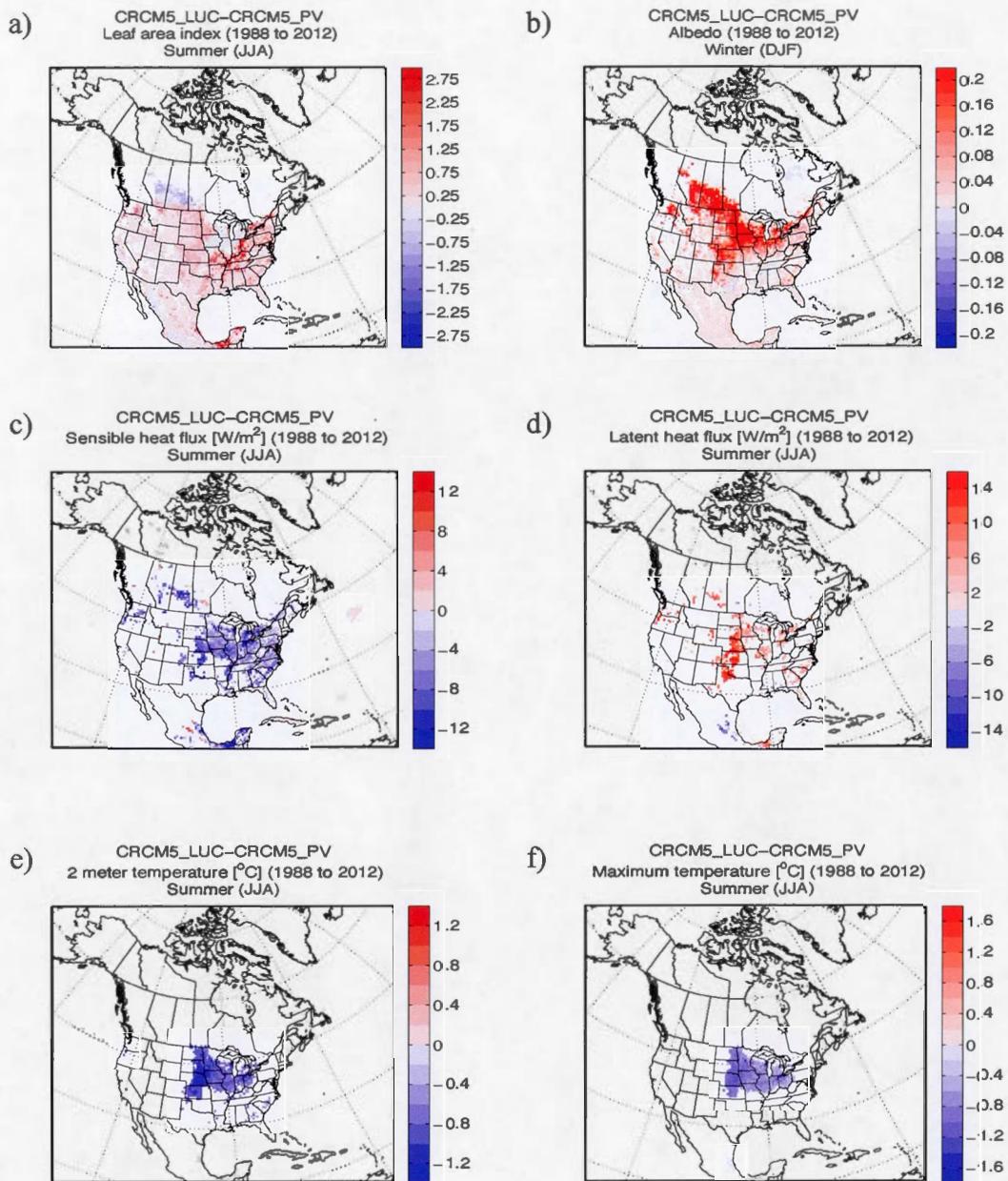
Figure 2.4 Differences between CRCM_LUC and CRCM_PV, for summer season, for (a) leaf area index, (b) albedo, (c) sensible heat flux, (d) latent heat flux, (e) two meter temperature, (f) maximum temperature, (g) minimum temperature and (h) soil temperature. Values are shown only for grid points where the differences are statisitcally significant at 95% confidence level.

g) CRCM5_LUC–CRCM5_PV
Minimum temperature [°C] (1988 to 2012)
Summer (JJA)

h) CRCM5_LUC–CRCM5_PV
Soil temperature [°C] (1988 to 2012)
Summer (JJA)
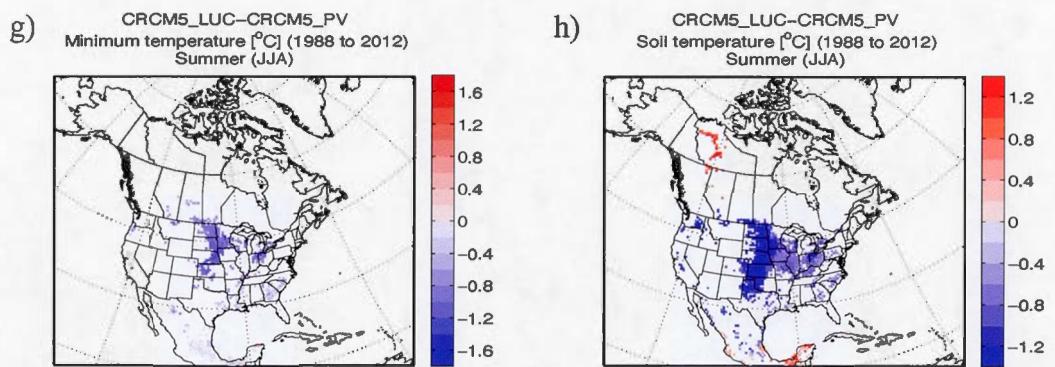
Figure 2.4 (continued)
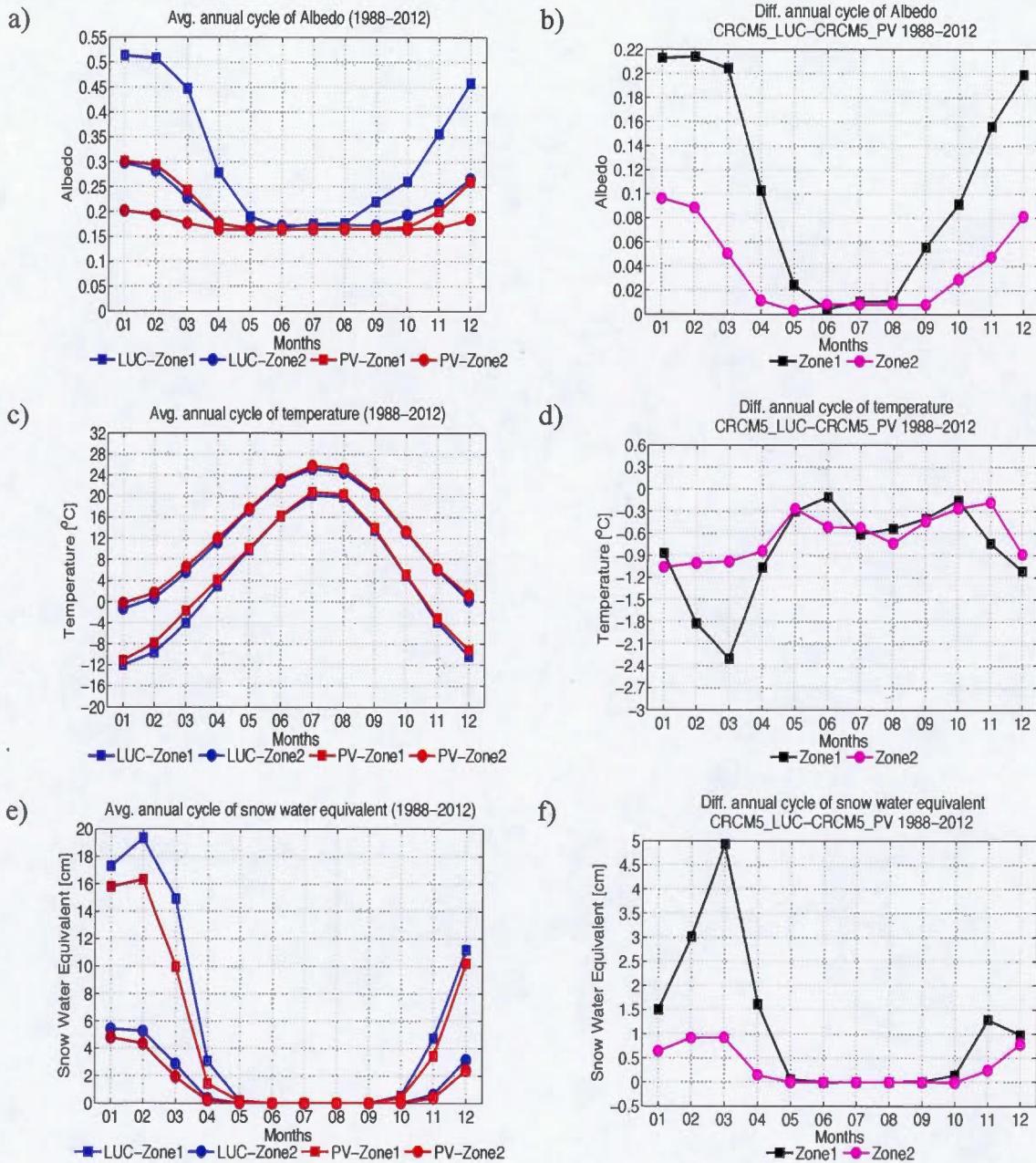
Figure 2.5 Left panels: average seasonal cycle for the 1988-2012 period for a) albedo, c) two meter temperature and e) snow water equivalent. Right panels: difference between CRCM5_LUC and CRCM5_PV seasonal cycle for b) albedo, d) two meter temperature and f) snow water equivalent.
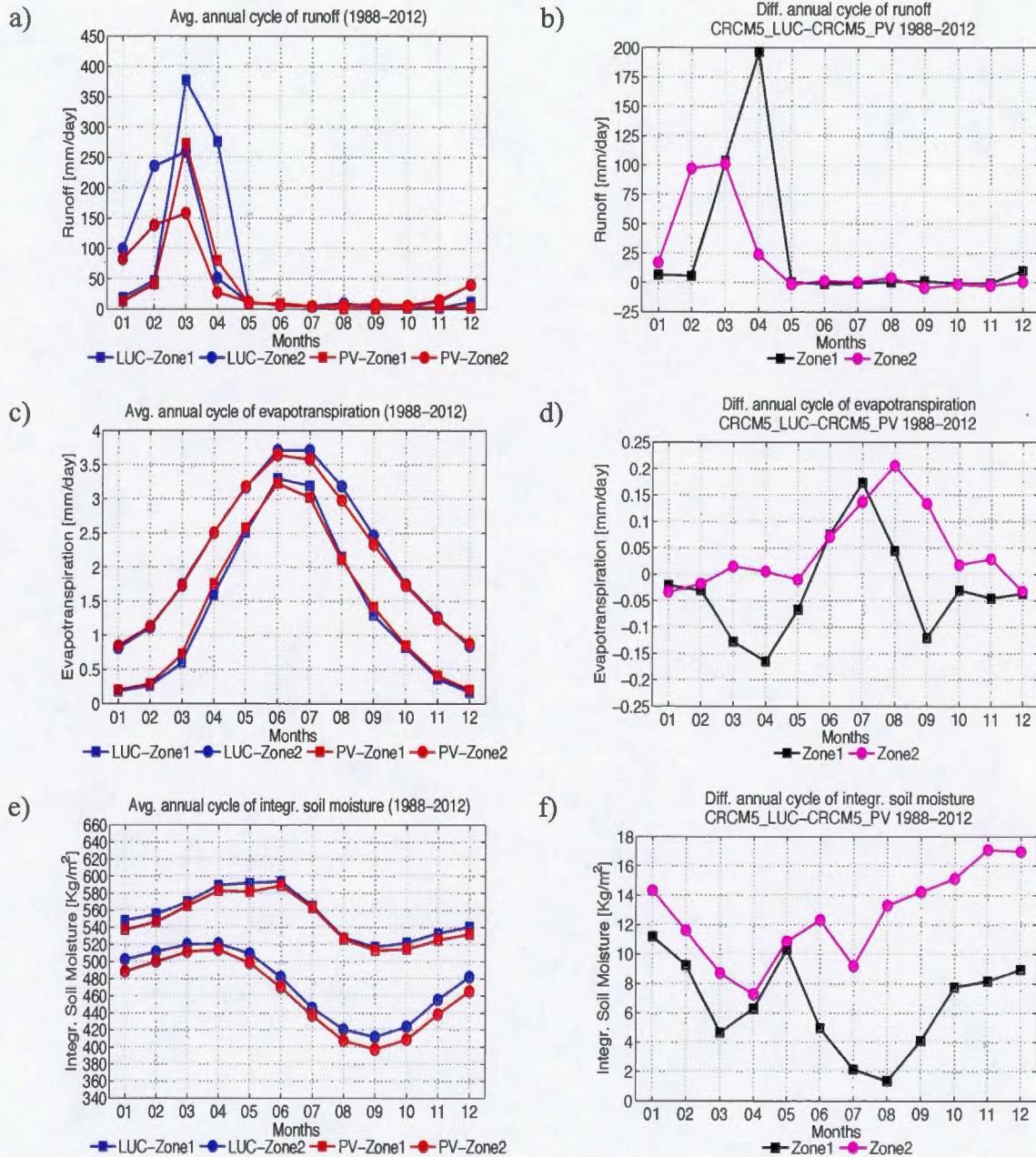
Figure 2.6 Left panels: average seasonal cycle for the 1988-2012 period for a) runoff, c) evapotranspiration and e) integrated soil moisture. Right panels: difference between CRCM5_LUC and CRCM5_PV seasonal cycle for b) runoff, d) evapotranspiration and f) integrated soil moisture.
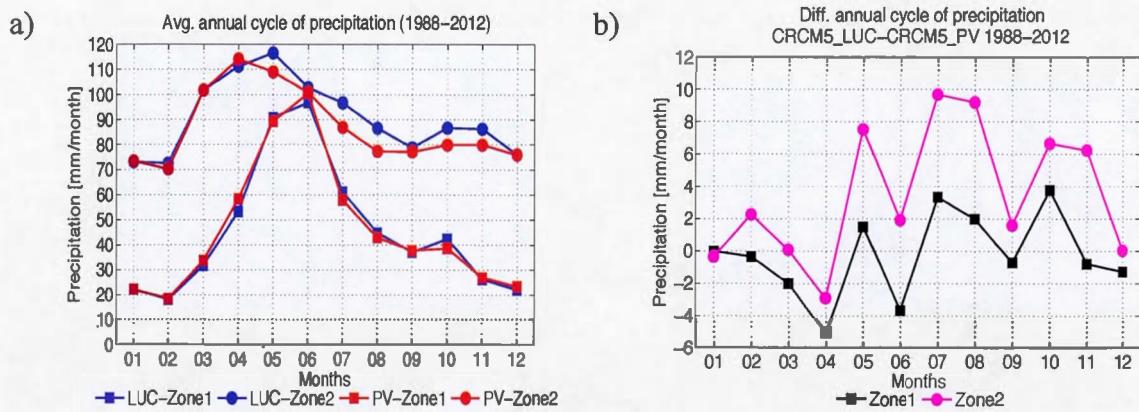
Figure 2.7 Left panel: average seasonal cycle for the 1988-2012 period for a) precipitation. Right panel: difference between CRCM5_LUC and CRCM5_PV seasonal cycle for b) precipitation.

SUPPLEMENTARY MATERIAL
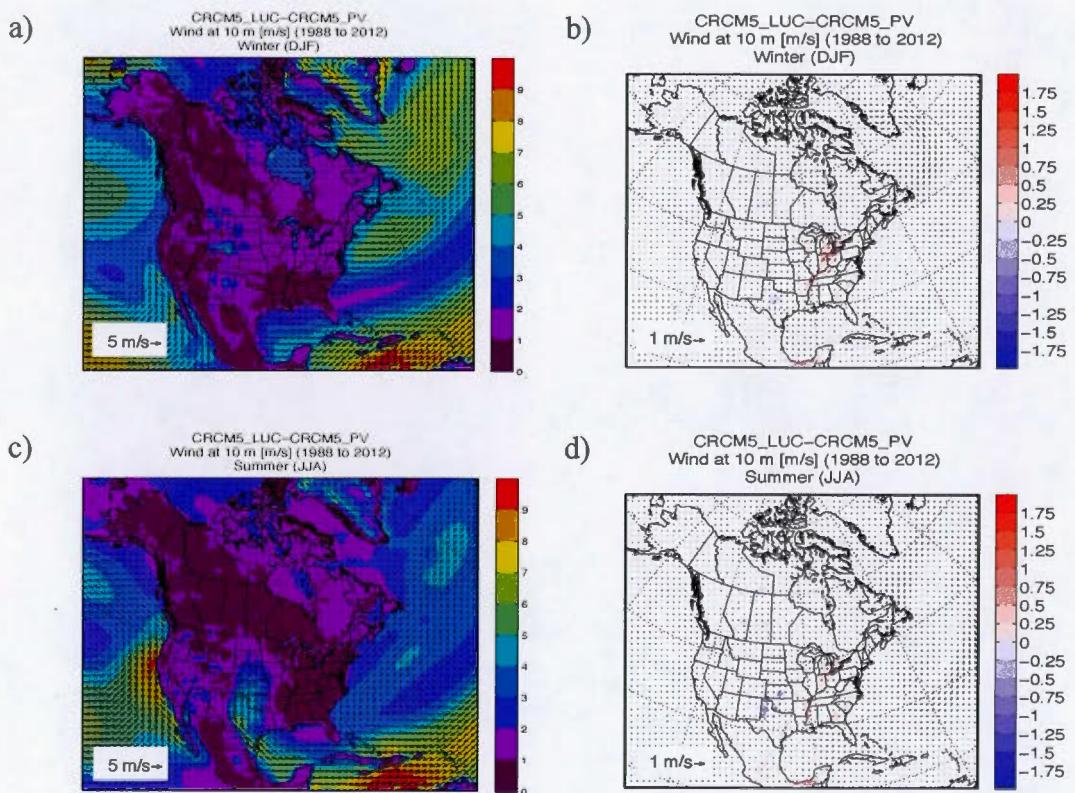
Left panels: seasonal average wind at 10 m for 1988-2012 period for (a) winter and (c) summer seasons. Right panels: differences between CRCM5_LUC and CRCM5_PV for 1988-2012 period for (b) winter and (d) summer seasons. Colour shading indicates grid points with statistically significant differences at 0.05 level.

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